V

ANL-77-XX-64

PRELIMINARY ASSESSMENT
OF
THE HEALTH AND ENVIRONMENTAL IMPACTS OF FLUIDIZED-BED COMBUSTION OF COAL AS APPLIED TO ELECTRICAL UTILITY SYSTEMS

February, 1977

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

operated under contract W-31-109-Eng-38 for the
U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) between the U. S. Energy Research and Development Administration, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona
Carnegie-Mellon University
Case Western Reserve University
The University of Chicago
University of Cincinnati
Illinois Institute of Technology
University of Illinois
Indiana University
Iowa State University
The University of Iowa

Kansas State University
The University of Kansas
Loyola University
Marquette University
Michigan State University
The University of Michigan
University of Minnesota
University of Missouri
Northwestern University
University of Notre Dame

The Ohio State University
Ohio University
The Pennsylvania State University
Purdue University
Saint Louis University
Southern Illinois University
The University of Texas at Austin
Washington University
Wayne State University
The University of Wisconsin

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights. Mention of commercial products, their manufacturers, or their suppliers in this publication does not imply or connote approval or disapproval of the product by Argonne National Laboratory or the U. S. Energy Research and Development Administration.

ANL-77-XX-64

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois
60439

PRELIMINARY ASSESSMENT
OF
THE HEALTH AND ENVIRONMENTAL IMPACTS OF FLUIDIZED-BED COMBUSTION OF COAL AS APPLIED TO ELECTRICAL UTILITY SYSTEMS

By

ANL SPECIAL TASK GROUP

February, 1977

ANL SPECIAL TASK GROUP

A task group approach was used by Warren Sinclair to assemble quickly the laboratory expertise needed for this assessment. The Divisions of Biological and Medical Research, Chemical Engineering, Energy and Environmental Systems, Environmental Impact Studies, and Radiological and Environmental Research participated in the assessment. Personnel making significant technical contributions were:

Charles D. Brown
Richard R. Cirillo
Peter A. Dauzvardis
Christopher D. Dux
Anthony J. Dvorak
Allan R. Evans
Paul Frenzen
Douglas Grahn

Ray R. Hinchman
Kenneth A. Hub
Julie D. Jastrow
Gregory C. Krohm
Barbara-Ann G. Lewis
Robert T. Lundy
Jon I. Parker
Kenneth E. Wilzbach
Thomas D. Wolsko

The experience of ERDA Environment and Safety personnel, gained in past and ongoing activities, provided some of the background used in the study. In particular, activities in the AES Divisions of

Biomedical and Environmental Research,
Environmental Control Technology, and
Technology Overview

were sources of information for the assessment.

The assessment was coordinated and assembled by Ken Hub under the general direction of John Hoover, both of the Energy and Environmental Systems Division.

CONTENTS

CONTENTS

Page

FIGURES

TABLES

ABSTRACT

The objective of this study was to assess the health and environmental impacts of fluidized-bed combustion of coal (FBC), specifically as applied to base-load generation of electrical energy by utilities. The study was a short-term effort that based its analyses on information derived from the experience of the group and/or quickly obtained from the literature. The approach was to compare Atmospheric Fluidized-Bed Combustion (AFBC) and Pressurized Fluidized-Bed Combustion (PFBC), with two current technologies: low-sulfur coal combustion (LSC) and flue gas desulfurization (FGD) used with high-sulfur coals. A wet-limestone process was selected as the FGD technology.

The impacts compared involved not only health and environment but also sociology, resource use, and dollar cost. Conditions for comparison were centered around a nominal date of 1988, when initial operation of commercial AFBC plants may occur. The PFBC has a later introductory date, a nominal 1995 (its impacts relative to other competitive technologies now in the R&D stages were not compared).

The public health impacts of FBC plants are expected to be quite similar to those for LSC and FGD plants because all appear to be able to meet federal emission standards; however, there are emissions not covered by standards. Hydrocarbon emissions are higher and trace element emissions are lower for FBC than for conventional technologies. For FBC, based on an analytical model and a single emission data point, the polycyclic organic material decreases the anticipated lifespan of the highly exposed public very slightly. Added health protection due to lower trace element emissions is not known. Although there is a large quantity of solid wastes from the generating plant, the environmental impact of the FBC technology due to solid residue appears lower than for FGD, where sludge management requires larger land areas and presents problems due to the environmentally noxious calcium sulfite in the waste. Fixing the sludge may become a requirement that increases the cost of wet-limestone FGD

but makes that system more acceptable. The potential for aquatic or terrestrial impacts from hydrocarbon emissions is low.

If application of AFBC technology increases the use of local high-sulfur coals to the detriment of western low-sulfur coal, a sociological benefit could accrue to the FBC (or FGD) technology, because impacts caused by western boom towns would decrease. The infrastructure of areas that mine high-sulfur coal in the Midwest are better equipped to handle increased mining than the West. No large differences in impacts due to resource use were shown among the technologies. The dollar costs of electrical energy produced were estimated in order to broaden the perspective of the assessments. Due to differences in delivered coal prices, the regional electrical costs vary among alternatives. The penetration of western low-sulfur coal into the utility markets is largely determined by transportation distances. FGD and AFBC options can be compared in cost on a national basis. Estimates show that the expected range of costs are quite similar.

The report is divided into four parts: an introductory statement; a brief description and summary technical comparison of the four technologies considered; a comparison of system impacts on public health, the environment, and supplementary areas affecting system development; and supporting materials. The latter section details and elaborates on the evaluations summarized in earlier sections.

1. INTRODUCTION

This report summarizes a short-term effort directed at assessing the health and environmental impacts of fluidized-bed combustion of coal (FBC) for electrical utility systems. To assess these impacts, certain bases and assumptions were established, including engineering design for FBC facilities, environmental standards, technology developments, and the selection of a method for assessing levels of health and environmental protection. Since the attractiveness of FBC technologies depends not only on health and environmental assessments but also on dollar costs, resources use, and sociological impacts, these form secondary considerations in the analysis. Potential environmental and health problems uncovered in this assessment should provide a basis for defining areas for R&D that will produce the data needed for a more complete analysis of the overall impact of FBC technologies on society. This section will briefly discuss some of these considerations in order to provide the perspective of the assessment.

The method selected for making the assessment was to compare the FBC technologies with other technologies presently being chosen by electric utilities for use in new generating plants that burn coal (i.e., low-sulfur coal combustion or high-sulfur coal combustion using flue-gas desulfurization methods). This choice is a reasonable approach for assessing the atmospheric fluidized-bed combustion (AFBC) technology because it is in the advanced stages of development, and must compete with current technologies; but use of the pressurized fluidized-bed combustion (PFBC) technology is further off in the future, and competition for acceptance by the utilities could come from still other coal-based technologies under development. However, because we could not adequately consider these other technologies due to the shortage of time, it was decided to make a comparison of the PFBC with the AFBC and with current technologies. As a minimum, the PFBC would have to compete with all of these.

The analysis was made by comparing one technology with another on a generating-unit basis. Expected generating-unit size is in the range of 500 to 800 MWe. Characteristics for the reference units are based on 500 MWe. However, some impacts are related to two-unit plants, in which case the output and impacts were for one year of 1000-MWe operation (these instances are clearly stated). We have assumed in our analysis that the generating plants would operate as base-load units, the environmental impacts being evaluated at a 75 percent capacity factor and the cost at a 65 percent capacity factor.

The utilities are planning to burn high-sulfur and low-sulfur coals in new plants. In order to meet air-quality standards, however, it is necessary to use flue-gas desulfurization (FGD) technology while burning high-sulfur coals. It is interesting to note that some state standards require FGD equipment even for burning coals that meet the federal New Source Performance Standards (NSPS) for sulfur emissions. There are many types of FGD processes. It was neither possible nor productive to analyze them all, so only one process is considered, namely, the wet-limestone process, which has been selected by a number of utilities for installation and operation in their systems.

Commercial application of AFBC is about ten years in the future. Technology development will probably result in FGD process improvements during this time. For example, the wet sludge from the scrubber is a waste that must be specially care for; however, it is possible that the sludge may be fixed (perhaps for 1 mill/kWh) so that leaching of noxious elements will not readily occur and the material will have sufficient strength for landfill disposal and subsequent wide use of the associated land. Regeneration of sorbent materials from the various sulfur-removal processes may also be possible; however, it was decided to consider "throw away" processes here because they tend to increase environmental impacts. If these processes appear to have acceptable impacts (by comparison with other sources of impacts within the system), the technologies may be accepted even though they are not regenerative.

The PFBC technology has the potential for sorbent regeneration and improved thermal efficiency, each of which makes the technology more attractive if the added cost is reasonable. For our assessment we used the easier-to-attain design without these advanced features, with a commercial introduction date of about 1955.

In one sense the developing technologies are also developing engineering designs, the developments being spurred, among other things, by the necessity to reduce health and environmental impacts and to meet competitive conditions. We could not factor changing designs into our analysis but only state our awareness of this. Also associated with engineering design is a probable thrust for even lower sulfur emission standards. Plants will be designed to meet the standards. Some knowledgeable people think that the current NSPS of 0.6 lb of sulfur per million Btu may be reduced to two thirds of that amount to help reduce impacts. At increased cost, such a standard could be attained by the FGD, AFBC, and PFBC technologies. However, the use of coals with higher levels of sulfur (>4%) would be reduced.

Our assessment emphasizes the power conversion facility in the coal-energy supply system. This is due to the fact that one is looking at a possible substitution of AFBC for FGD, presumably with the same high-sulfur coal. Where AFBC is compared with use of low-sulfur coal (LSC), a change in the source of coal would occur. This change in the system would cause differential mining and transportation impacts. We attempted to maintain a systems outlook and to quantify these impacts for one situation.

Our approach to the definition of R&D needs was to flag these requirements as we made our analysis when we saw a lack of the information needed to make a choice or define impacts. We did not attempt to delineate whether the R&D would be obtained from an ongoing program.

Finally, although our approach in assessing health and environmental effects was to compare impacts among technologies, and focused on differential impacts, we attempted to maintain an awareness of the absolute magnitude of impact. Thus the question was asked, "Can society live with the level of impacts caused by use of the technologies?" For the most part, this question reverts back to standards and to possible changes in the future as determined by the never-ending balancing of costs and benefits.

The report is divided into three sections: Descriptive Technical Comparison of Systems, Comparison of Impacts Among Systems, and Supporting Materials. The descriptive technical comparison gives a brief overview of the technical characteristics of the various coal-burning facilities under consideration. Details of the systems can be found in the section containing the supporting materials. The comparison of impacts section summarizes health, environmental, societal, resource use, and dollar cost impacts. These impacts are reported in detail in the supporting materials.

2. BRIEF TECHNICAL DESCRIPTION AND COMPARISON OF THE TECHNOLOGIES

This report section will describe and compare, on a technical basis, the four coal combustion alternatives considered in the assessment. All of the alternatives will, of course, not be viable options to utilities throughout the U. S. because of cost and local factors. Each technology can be thought of as an individual element in an energy-supply system that consists of all parts of coal-energy utilization, specifically:

- Mining and fuel preparation,
- Fuel transportation,
- The electrical generating plant,
- Waste disposal, and
- Electric power transmission and distribution.

Major supplemental material supplies (e.g., limestone) are considered direct adjuncts to the system.

The emphasis in this section is on the coal combustion technology in the electrical generating plant and on closely related facilities such as solid waste disposal. Portions of the overall system that will vary among the alternatives will cause differences in the expected impacts. Electric power transmission and distribution impacts are not included in this study. Coal extraction and transport will not be characterized here; their associated health impacts are discussed in Chapter 4.

2.1 CHARACTERIZATION OF COALS

Because many aspects of coal conversion technologies depend upon the characteristics of the fuel, the general properties of the coals assumed for this assessment are characterized in Table 2.1. Two basic coal categories are

Table 2.1. Coal Characteristics[a]

	Midwestern High-Sulfur	Eastern High-Sulfur	Western Low-Sulfur	Eastern Low-Sulfur
Proximate Analysis, wt%				
Moisture	7.0	3.0	27.0	5.0
Volatile matter	33.0	28.0	32.0	24.0
Fixed carbon	48.0	62.0	35.0	65.0
Ash	12.0	7.0	6.0	6.0
Sulfur, wt%	3.0	2.2	0.5	0.6
Heat content, Btu/lb	12,000	14,000	9,000	14,500

Basis: V. E. Swanson et al., *Collection, Chemical Analysis, and Evaluation of Coal Samples in 1975*, U. S. Geological Service, 1976.

[a] The reader should refer to Tables 2.2 (fuel input), 2.3 (air emissions), and 2.4 (solid wastes) for a comparative listing of residuals, and to Section 4.6 for detailed background information.

considered: high-sulfur and low-sulfur. A distinction is made between western low-sulfur subbituminous coal (e.g., from Wyoming or Montana) and eastern (Appalachian) low-sulfur coal, because their characteristics are entirely different. The characteristics listed in the table are for illustrative purposes and are intended only to reflect general regional values; in reality, one might expect wide variations in coal compositions within the geographic regions and in the individual coal seams. Thus, it is possible for a region with predominantly high-sulfur coal reserves to have low-sulfur coal deposits, although these reserves are generally limited. Sections 4.5.2 and 4.5.3 discuss the topics of coal supply and cost.

The trace element composition and content of coals vary among regions and seams. In general, Montana and Wyoming coals have lower concentrations of trace elements than coals from the Eastern Interior Region (e.g., Illinois).

Western low-sulfur coal has a somewhat lower heat content and a substantially higher moisture content than high-sulfur coals. For the purpose of this assessment, consideration of fuels will generally be limited to western low-sulfur and Eastern Interior Region high-sulfur coals.

2.2 CHARACTERIZATION OF REFERENCE PLANTS

The technical descriptions that follow are based on a unit 500-MW plant that supplies power to a conventional electric utility transmission grid. The reference plant site in each case will contain the combustor/steam generator, steam turbine and electric generator, condensor cooling system with cooling towers, coal handling and storage facilities, environmental control facilities, stacks, fans, and ash handling facilities. Variations in these elements among the technologies are noted.

2.2.1 Atmospheric Fluidized Bed Combustion (AFBC)

Atmospheric fluidized bed combustion is an advanced combustion technique in which crushed coal burns in the presence of crushed limestone while held in suspension by upward-flowing combustion air. The technique has two advantages. The first is that rapid heat transfer and high heat-release rates at reduced temperature can be obtained, so that boiler tubes can be imbedded in the combustion zone, resulting in smaller boilers. The second is that the limestone acts as a sorbent to chemically remove sulfur dioxide directly from the combustion zone. As its name implies, AFBC occurs at near atmospheric furnace pressure.

An AFBC utility power plant is envisioned to consist of four separate modular units, each of which is composed of four fluidized-bed cells, plus one high-temperature carbon burnup cell (CBC), which is required to prevent appreciable loss of coal energy from unburned coal leaving the combustor. Steam from each of the modules is combined to drive a single conventional steam turbine/generator. The modular concept, which is required because of bed size limitations, is also expected to provide the station operator with some flexibility in meeting partial load demands and reducing total plant maintenance outages by allowing for the removal of individual modules from service. Stacks, fans, and cooling systems would be equivalent to those in conventional coal combustion systems. The overall heat rate of the AFBC plant would be about 9550 Btu/kWh, equivalent to a thermal efficiency of approximately 36 percent.

The AFBC plant is expected to be capable of burning a wide range of fuels. Each plant is, however, designed to accept a specific fuel with some margin for variations, which is common practice in conventional boiler design. At present, there is some uncertainty as to whether the developing AFBC technology can burn some low-sulfur (<2% ?) coals using limestone beds. Experiments on widely characterized low-sulfur fuels are required and, depending upon the results, additional process development may be required.

Approximately 90 percent removal of SO_2 is achievable using limestone in Ca/S molar ratios of 2 to 4 (depending upon the reactivity of the limestone). It is believed that if a CBC is used, SO_2 removal may be limited to 85 percent. For most coals, such removal rates would result in SO_2 emission rates considerably below NSPS. In most situations the facility will be designed and operated to meet the standards--i.e., no more sulfur will be removed than is necessary.

Current data indicate that NO_x emissions could conceivably be about 350 to 450 ppm, depending on the extent of CBC use. NSPS correspond to 525 ppm. Dust loadings in the flue gas could be 2 to 5 times higher than in conventional combustion. Because of the anticipated high electrical resistivity of the fly ash, conventional coal electrostatic precipitators (ESP) would be inadequate, thus requiring hot ESPs or even fabric filters. Because of the current lack of definitive information on AFBC particulate control, it will be assumed that AFBCs can meet the current NSPS for particulates of 0.1 lb/10^6 Btu. Some data suggest that trace-element airborne emissions will be less than in conventional plants.

Because of the temperature and oxygen conditions in the combustor, more unburned hydrocarbons are expected than in conventional plants. One data point suggests that polycyclic organic material (POM) emissions will be 2 to 3 mg per million Btu.

The spent sorbent removed from the bed is largely a mixture of CaO and $CaSO_4$, their proportions depending on the Ca/S ratio used. A recent demonstration program has shown that regeneration of the spent stone is not economic, so once-through use is assumed for this assessment. Since leachates from the spent sorbent have a high pH and show considerable extraction of calcium and sulfate, disposal presents problems that are not yet resolved on an engineering scale.

2.2.2 Pressurized Fluidized Bed Combustion (PFBC)

A 500-MW PFBC power plant would be fundamentally similar in basic design to the AFBC plant, i.e., it would utilize a modular configuration for the beds, fuel and sorbent would be injected into the beds, and steam collected from the modules would drive a single steam turbine. The major distinction is that the beds would be under about 10 atmospheres pressure. The high-pressure, high-temperature combustion gases from the modules would be combined and expanded through a single gas turbine that would provide about one-fifth of the station's gross electrical output. The overall station heat rate of the PFBC plant would be about 8970 Btu/kWh, corresponding to an overall thermal efficiency of about 38 percent. According to some estimates, the efficiency of an advanced PFBC plant could approach 45 percent, but advanced plants will not be considered in this assessment.

The PFBC will be capable of burning a wide range of low- and high-sulfur coals. No problem in burning low-sulfur coal is anticipated.

For the sorbent in Ca/S molar ratios of 1.5 to 2, depending upon the reactivity of the dolomite, approximately 90 percent removal of SO_2 is achievable. Because of the pressure conditions, dolomite is preferred to limestone. About 1.84 times as much dolomite as limestone (by weight) is required to provide a given weight of calcium. Emission of nitrogen oxides will fall in the range of 150 to 300 ppm, well within current NSPS. Particulate loadings in the gas from the combustor will be lower than for the AFBC but still higher than for conventional combustion. It is assumed here that particulate removal to levels an order of magnitude better than current NSPS will be necessary prior to the hot gas expansion through the turbine, in order to minimize erosion of the turbine blades. The particulate control technology required to achieve these levels is not currently available, but is assumed to be operable in the reference case. POM emissions are expected to be similar to those from AFBC: 2 to 3 mg/10^6 Btu.

As in the case of AFBC, the dolomite sorbent in PFBC will be utilized in a once-through mode. The spent sorbent is a mixture of $CaSO_4$, $CaCO_3$, MgO, and a small amount of CaO; the proportions depend on the Ca/S ratio. Spent sorbent disposal problems are similar to those in AFBC, but somewhat less severe because of the lower solubility of the magnesium salts.

2.2.3 Conventional Combustion of Low-Sulfur Coal (LSC)

The technology of low-sulfur coal use is based on a conventional state-of-the-art plant consisting of a single pulverized coal furnace/steam generator with NO_x control, a single steam turbine/generator set, and a cooling system. The primary criterion for the coal is a sulfur content sufficiently low to attain current NSPS for SO_2 without the aid of additional control devices, i.e., less than 0.6 lb/10^6 Btu. Overall plant heat rates for the best state-of-the-art plants burning eastern LSC approach 8800 Btu/kWh (about 39% thermal efficiency). Heat rates for burning western coal are higher, about 9550 Btu/kWh (about 36% thermal efficiency) because of the higher moisture content of the coal and additional pulverizer capacity needed to compensate for the lower heat content.

For this and for the other reference plant, the rate of SO_2 emission is about equal to the NSPS, 1.2 lb/10^6 Btu. The plant will emit NO_x in the range of 300 to 400 ppm using low excess air and staged combustion. The high electrical resistivity of the fly ash makes collection difficult, but particulate emissions can be kept within 0.1 lb/10^6 Btu. Total hydrocarbon emissions will be about 0.2 lb/ton of coal. POM emissions range from 0.2 to 1 mg/10^6 Btu.

As there are no spent sorbents to dispose of in this case, solid wastes from LSC plants will only consist of bottom ash and collected fly ash.

2.2.4 Conventional Combustion of High Sulfur Coal with Flue Gas Desulfurization (FGD)

A 500-MW FGD power plant would be essentially the same as the LSC plant, but would have the capability of burning coals with considerably higher sulfur contents because 80 to 90 percent of the sulfur in the flue gas would be removed by a chemical scrubbing process. It is assumed that a "throw away" limestone slurry scrubber will be used in a closed loop (water is recycled to scrubber).

The emission of oxides of nitrogen from the FGD plant will be equivalent to those from the LSC plant, in the range of 300 to 400 ppm. Particulate emissions will be within NSPS of 0.1 lb/10^6 Btu. POM emissions will be equivalent to those from LSC, 0.2 to 1 mg/10^6 Btu.

In limestone scrubbing, the calcium salts are rejected in the form of a slurry that is difficult to dewater beyond 40 percent solids. Even if the sludge is mixed with fly ash, it can only be dewatered to the extent of 50 to 60 percent solids, insufficient for landfill suitability. Leachates from such sludges contain sufficient trace metals that groundwater contamination may result if disposal ponds do not have impervious linings. Although not included in the reference plant, the sludges can be chemically stabilized so that they have sufficient compressive strength to be suitable for landfills.

2.3 COMPARISON OF ALTERNATIVES

A comparison of fluidized-bed and conventional combustion alternatives can be achieved on four levels:

1. Overall system - Considers each technology alternative as part of the coal "supply" system: fuel source, fuel transport, etc.

2. Plant and Components - Includes comparison of the size and nature of operating conditions of individual components, particularly coal combustors. Mode of operation of the unit, as well as familiarity

of operation by utility personnel and utility acceptance, should be also considered.

3. Resource Inputs - Covers fuels, water use, and sorbent use.

4. Environmental Residuals - Includes air, solid waste, and water effluents.

2.3.1 Overall System

2.3.1.1 Fuel Source

It has been estimated that over 90 percent of the U. S. reserves of low-sulfur steam coal lie west of the Mississippi River, while vast reserves of high-sulfur and high-Btu-content coal lie in the East and Midwest, which are some of the high electrical demand areas of the country. It is evident that any technology option that can utilize these high-sulfur coal reserves in an environmentally acceptable manner is advantageous.

The FBC and FGD alternatives, with their abilities to fire higher sulfur content coals, could utilize these eastern coals and reduce western LSC demands.

2.3.1.2 Transportation Modes

Fuel can be transported from the mine to the plant by conventional alternatives--train (unit or otherwise), barge, slurry pipeline, conveyor, or truck--depending upon the relative locations and availabilities of transportation capacity.

With the use of high-sulfur coals, power plants in the eastern U. S. would decrease the future burden on railroad transportation. Also, the need would decrease for such projects as coal slurry pipelines bringing low-sulfur coal distances of 1000 miles or more from water-scarce western U. S. regions.

2.3.2 Plant and Components

2.3.2.1 Combustors and Steam Generators

Aside from differences in residuals, the difference in furnace design between FBC and conventional power plants could possibly result in differences in plant layout, plant cost, plant construction time, and plant operation. Fluidized-bed boilers are more compact in terms of bed area than conventional furnaces, so some advantage in construction cost could be gained. This is projected to be particularly true of PFBCs: their higher operating pressure allows compact modules, which could foreseeably be shop-fabricated to save field-fabrication costs and reduce construction time.

Balanced draft firing using both forced-draft and induced-draft fans currently is used in conventional pulverized coal furnaces and will be used in AFBC plants. Electric utilities are most familiar with this type of combustion. Fuel combustion under pressure, as in PFBC, will be new to utility operation and could cause safety concerns.

2.3.2.2 Turbines and Generators

The AFBC, PFBC, LSC, and FCD options all utilize the proven technology now used in conventional steam turbines and generators. In addition, a gas turbine-generator-compressor is required for PFBC technology. Designing gas turbines to withstand prolonged service under PFB power plant conditions, where erosion of the blading by particulates occurs, is a major development problem.

2.3.2.3 Cooling Systems

Conventional cooling systems (i.e., condensers and cooling towers, etc.) are applicable to all four technology options.

2.3.2.4 Particulate Control Devices

Particulate emissions can be controlled from conventional and AFBC power plants using available state-of-the-art control devices. It is not currently possible to meet desired particulate loadings in PFBC flue gases imposed by the limitation of gas turbines.

2.3.2.5 Stack Conditions

Physical conditions at the stack exit will be comparable for all four alternatives. Since the air/fuel ratios will be similar (15 to 20 percent excess air in all cases) and exit temperatures are similar (250° to 300°F), flue gas exit velocities and atmospheric pollutant dispersion can be considered equivalent.

2.3.3 Utility Acceptance

A prominent engineering consulting firm recently conducted a survey of 14 electric utilities to ascertain their attitudes on FBC. The general response indicated that there was insufficient operating experience to allow any type of commitment to FBC, although most felt FBC would find application in electricity generation in the future.

2.3.4 System Inputs

2.3.4.1 Fuels

Fuel for the conventional LSC option is limited in many regions to coals with sulfur contents lower than 0.6 lb/10^6 Btu; for a typical western subbituminous coal with a heating value of 9000 Btu/lb, this corresponds to less than about 0.5 percent sulfur. The FBC and FGD options are not as constrained by the sulfur content of the fuel, although the AFBC may have difficulty burning fuels with sulfur contents less than about 2 percent, and additional development would be required. Hypothetical annual coal inputs for the four options are presented in Table 2.2. The approximately 30 percent increase in coal tonnage input for the LSC option is needed due to the significantly lower heat content of most typical western low-sulfur coals.

2.3.4.2 Water Use

Minimal differences in water input are expected among the four options. Handling of the bottom ash and spent sorbent in dry form rather than wet as in conventional plants will save maybe a few percent of the input flow. A potential increase in PFBC thermal efficiency from 38 percent to about 45 percent, if achieveable, could result in about a 25 percent reduction in evaporative cooling water makeup.

2.3.4.3 Limestone and Dolomite

Conventional combustion of low-sulfur coal needs no sorbent; relative requirements for the FBC systems are shown in Table 2.2. AFBC has nearly three times the required tonnage of FGD, and PFBC has over twice the input of FGD. These high volumes of stone would make the siting of AFBC and PFBC plants sensitive to ample reserves of limestone or dolomite.

Table 2.2. Fuel and Sorbent Input for FBC and Conventional Plant Alternatives

Technology	Thermal Efficiency, %	Ca/S (mole/mole)	Coal Input, 10^3 tons/yr	Sorbent Input, 10^3 tons/yr	Sorbent
AFBC[a]	36	3	1323	349	Limestone
PFBC[a]	38	1.5	1245	290	Dolomite
FGD[a]	37	1.2	1280	135	Limestone
LSC[b]	36	-	1760	-	-

[a] Basis: 500 MW, 0.75 annual load factor; coal with heat content of 12,000-Btu/lb, 12 percent ash, 3 percent sulfur, 80 to 90 percent sulfur removal.

[b] Basis: 500 MW, 0.75 annual load factor; coal with heat content of 9000-Btu/lb, 6 percent ash, 0.5 percent sulfur.

The use of a solid sorbent increases the problems of solids handling and necessitates provisions for additional unloading facilities, additional storage capacity, and an increase in the amount of grinding and crushing machinery at the plant. Dependence on a solid sorbent makes the utility more dependent on external supply for continuity of service.

2.3.5 System Effluents

2.3.5.1 Air Emissions

Table 2.3 describes the comparative atmospheric emissions from fluidized-bed and conventional power plants.

SO_2

All four options are expected to attain the SO_2 emission levels allowed by New Source Performance Standards. AFBC, PFBC, and FGD can potentially reduce emissions below NSPS and below that of LSC. The LSC option is quite

Table 2.3. Comparative Projected Atmospheric Emissions from Fluidized-Bed and Conventional Plant Alternatives

Technology	SO_2	NO_x	Particulates
AFBC	$90\%^+$ removal; meets current NSPS*	350–450 ppm	Projected to meet NSPS
PFBC	$90\%^+$ removal; meets current NSPS	150–300 ppm	~0.01 lb/10^6 Btu (est. loading limit for gas turbine)
LSC	Meets current NSPS	300–400 ppm	Meets NSPS
FGD	90% removal; meets current NSPS	300–400 ppm	Meets NSPS

*New Source Performance Standards (NSPS):
SO_2: 1.2 lb/10^6 Btu
NO_x: 0.7 lb NO_2/10^6 Btu (approx. 525 ppm)
Particulates: 0.1 lb/10^6 Btu

restricted in its means of limiting SO_2 emission rates. Future imposition of a stricter NSPS could effectively reduce the reserves of coal that would meet standards and limit the installation of the LSC alternative. In such an event, FBC and FGD would be expected to fill the void for new capacity additions.

NO_x

State-of-the-art conventional power plants can achieve levels of NO_x within current NSPS limits. The AFBC with a carbon combustion cell will also satisfy NSPS. PFBCs have inherently lower emissions of NO_x, about half those of conventional pulverized coal boilers.

Particulates

Conventional power plants have the capability of achieving NSPS limits for particulate emissions; AFBC is expected to be able to achieve these limits, but somewhat advanced fabric filter technology may be required. Due to the severe particulate loading limitations expected to be imposed by the gas turbine, the emissions of particulates from PFBC power plants are projected to be well within current standards, perhaps even an order of magnitude lower. Achievement of these limits under PFBC conditions is impossible with current technology.

Hydrocarbons

Total hydrocarbon emissions from furnaces burning pulverized coal are low (ca. 0.02 lb/ton coal), even when low NO_x combustion controls are in use. The utility boilers for LSC and FGD are also only minor sources of POM, with emissions in the range of 0.2 to 1 $mg/10^6$ Btu. One preliminary data point suggests that POM emissions from FBC plants may be somewhat higher than in conventional combustion--in the range of 2 to 3 $mg/10^6$ Btu.

Trace Elements

In general, the emission of atmospheric trace elements will be lower for the FBC alternatives. Although approximately 90 percent of all mercury will be emitted in both cases, significant retention of F, Cl, and Br will be expected to occur on the FBC limestone sorbents. Retention of As and Se may also occur.

2.3.5.2 Water Pollutant Emissions

No information regarding water pollutant emissions from fluidized-bed power plants is available. Similarities between FBCs and conventional power plants in cooling systems, boiler cleaning, and feedwater treatment should result in comparable emission characteristics. The only exception to this may be in the area of bottom ash handling: Ash and sorbent are handled dry in FBC; ash would probably be handled wet in conventional systems. Water released from wet ash handling may result in the possible emission of several trace elements leached from the ash. Levels of total suspended solids and chlorides might also be expected to be lower from FBCs.

2.3.5.3 Solid Wastes

In Table 2.4 the amounts of solid wastes that might be expected from each of the alternatives are quantified.

About the same amounts of solid wastes are generated from AFBC and PFBC. Some environmental problems could occur with spent AFBC sorbents, as the high CaO content may create high alkalinity in runoff waters. No such problem is expected to occur from PFBC wastes. No data are currently available on the leachability of trace elements from FBC solids. In addition, the general sorbent disposal method has yet to be determined.

Table 2.4. Comparative Estimated Solid Waste Emisssion From Fluidized-Bed and Conventional Plant Alternatives

Technology	Dry Spent Sorbent, 10^3 tons/yr	Dry Ash, 10^3 tons/yr	Total Solids, 10^3 tons/yr	Total Fixed @ 80% Solids, 10^3 tons/yr	Comments
AFBC	291	159	450	NA	Could have pH problem
PFBC	315	150	465	NA	No ph problem expected
FGD	171	154	325	405	Sludge mixed with ash
LSC	NA	105	105	NA	

The wastes from FGD plants would be somewhat less than FBC wastes, but these wastes are in a sludge form, and some type of chemical stabilization would be required to enable use of the waste in landfills.

Solid wastes from LSC are bottom and fly ash.

2.4 STATUS OF FLUIDIZED-BED TECHNOLOGY

The current status of FBC development is condensed in the following table. (Details can be found in report Section 4.6.1.3.)

Table 2.5. Ongoing Projects Related to Fluidized-Bed Combustion

Contractor	Sponsor	Project Objectives and Scope
Pope, Evans & Robbins	ERDA	30-MW AFBC pilot plant at Rivesville, W. Va. Process, operation, and component studies: optimization of ash handling, coal and sorbent feed systems.
Morgantown Energy Research Center	ERDA	Proposed construction of intermediate-size AFBC Component Test and Integration Unit (CTIU) at Morgantown, W. Va. Component and operations studies: develop technology for vertical stacking of beds, boiler tube configurations and materials testing.
Curtiss-Wright	ERDA	Design, construction, and operation of a 10-MW PFBC pilot plant at Woodbridge, N. J.: provide operating, engineering, economic data.
To be determined	ERDA	Construction of PFBC-CTIU facility to provide components testing and support of above pilot plant program.
To be determined	ERDA	Feasibility study, design, construction, and operation of prototype AFBC units for industrial application.
To be determined	ERDA	Evaluate the applicability of AFBC techniques to conversion of existing power generation systems.
ANL, MITRE Corp., MIT	ERDA	Engineering support studies: laboratory studies; systems analysis for regeneration, waste disposal, environmental control. Development of analytical models of processes.
Battelle	EPA	Primary environmental assessment of FBC: comprehensive analysis of emissions, assessment of control technology, environmental impact analysis, development of environmental R&D programs.
Ralph Stone & Co.	EPA	Study of solid and liquid FBC wastes.

Table 2.5. (Continued)

Contractor	Sponsor	Project Objectives and Scope
TVA	TVA, EPA	Study of solid waste processing: characterization, identification of leachability, treatment technology studies, spent sorbent marketability studies.
Exxon Research and Engineering	EPA, FEA	Study of economic, engineering, and environmental feasibility of application of FBC to industrial sector.
TVA	TVA, EPA, NASA, NSF, ERDA	Develop conceptual designs and comparative capital and operating costs for AFBC, PFBC, and FGD powerplants. Part of ECAS study.
EPA - RTP	EPA	Construction and testing of small-scale atmospheric combustor: comprehensive emissions testing, evaluation of analytical sampling techniques, and investigation of control devices.
Dow Chemical	EPA	Evaluation of system size on FBC emissions for information on scale-up to commercial size.
Pope, Evans & Robbins	HUD, NASA, DOC (NBS), EPA, HEW DOD, ERDA	Modular Integrated Utility Systems: design, fabricate and test 0.5-MW AFBC unit for use in intercommunity energy modules.
EPRI	EPRI	Study of heat transfer, solids distribution, corrosion of boiler tubes.
TVA	TVA	Preliminary design and support studies for a 200-MW AFBC demonstration plant.
Stone & Webster, Burns & Roe	ERDA	Conceptual design work for FBC power plants.

3. SUMMARY COMPARISON OF IMPACTS AMONG SYSTEMS

The findings of the study regarding major areas of impact are summarized here on a comparative basis. Details can be found in Section 4, "Supporting Materials."

The results obtained have depended on many assumptions; in some instances experimental data are represented by as few as one point. The results are also dependent on current engineering design and proposed methods for handling and treating wastes. These could change, however, as the technology for the FBC is developed, and are dependent on costs and on the competitive position of the technology. The relative competitive positions among the technologies are unknown, however, as all of the options appear capable of meeting federal standards; features to enhance acceptance by utility customers may well center on plant items that do not influence impacts on the health and environment.

The impacts are summarized under the headings of health, environment, society (limited sense), resource use, and dollar cost. There is no meaningful, simple way tc combine these impacts into a single value or ranking. An overview statement that perhaps sums up the assessment is that the AFBC technology has acceptable impacts in that it has some advantages and disadvananges compared with conventional technologies; the thrust for its development is not based on a large reduction in environmental and health impacts, but possible improvements in utility conversion plant operation with an improvement in dollar costs.

3.1 HEALTH EFFECTS

3.1.1 Public Health

Any coal-fired power plant meeting NSPS, whether FBC or otherwise, may be expected on a long-term basis to increase the total mortality rate in the areas of heavier environmental impact by about 15 to 50 deaths per million exposed persons per 1000 MWe-year. These deaths are generally attributed to the sulfates, particulates, hydrocarbons, and related by-products released into the environment and continuously inhaled by the public.

The relatively higher amounts of hydrocarbons released by FBC systems gives them a slightly greater potential for causing lung and stomach cancers than conventional systems. Within the plants there are particles that must be removed to meet standards. The CaO and $CaSO_4$ particles, projected to make up most of the increased loading, are probably less dangerous than the particles emitted by conventional systems; however, this would not necessarily be true for the soot particles. Depending on their chemical composition, they may enhance risks of stomach cancer in the exposed population.

With respect to health risks to the general public from airborne pollutants, FBC does not appear to have any major advantages or disadvantages compared with other coal combustion technologies. The slight disadvantage it suffers in the area of hydrocarbon emissions may be offset by its lower trace-element emissions.

The foregoing assessment, however, must be taken as educated guesswork. Experimental work and field epidemiological studies analogous to those done for radiation and for tobacco smoke are needed to establish the toxicity of plant effluent streams--both alone and in the presence of other forms of air pollution--for all forms of coal combustion technology. This is especially needed for advanced technologies; conventional systems, having already contributed to past and current levels of air pollution, have provided some of the firsthand knowledge needed for assessments. We have no direct experience at all with FBC.

3.1.2 Analysis of Public Health Impacts

The appropriate measurement used for a comparison depends on the comparison intended. We have calculated two measures of health impact: the expectation of life (e_0), which is the expected life span of an individual exposed for life to the pollutant considered, and the change in the annual death rate per million population which would be observed over a 25-year period with the same initial population.

For the following estimation of impacts, one-to-one comparisons of the technologies were unnecessary. For many pollutants, there now exist emission standards that must be met by all new power plants irrespective of the technology employed. Analytical Models A and B (see table which follows) are both based on pollutants thus regulated, so there is little to be gained by comparing health effects from these pollutants for the various combustion methods. We therefore present only general results for a hypothetical 1000-MWe power plant meeting the indicated standards. For hydrocarbons, however, there are no NSPS or other regulations, so we present results comparing the AFBC with conventional combustion and flue gas desulfurization.

The pollutant plume does not spread evenly over the area of impact--defined, for the analysis, as a circle with a radius of 50 miles centered around the point source. Our results are therefore divided into two parts (see table). The first is calculated on the assumption that the population is distributed evenly throughout the impact area, and that the mean exposure is the mean concentration to be found in the area. The second is calculated on the assumption that the entire population lives in that portion of the study area which contains the higher concentrations of pollution, and can therefore be taken as something of an "upper limit" to the effects discussed. Such areas, it should be noted, are characteristically valleys or other flat areas surrounded in part by physical barriers to air movement, and are therefore also likely to be places considered desirable as locations for human-oriented activities.

The models used here all have disadvantages and peculiarities which should be mentioned. Model A was derived with the use of reasonable measurements of complicating social and economic factors, but very poor estimates of population exposures to the pollutants studied. It can therefore be expected on statistical grounds to underestimate the relative importance of pollution variables. Model B is based on a study which was able to get reasonable measures of pollution exposure, but which suffers from small-number problems in

Table 3.1. Results From the Public Health Impact Analysis for a 1000-MWe Plant

		Average Values for 50-mile-radius Circle				Highly Impacted Subarea			
		Expectation of life (e_o)		Deaths/10^6		e_o		Deaths/10^6	
		M	F	M	F	M	F	M	F
Baseline Values (Berkshire Co., Mass., White Population, 1970)		68.861	75.541	11,583	10,705	Same			
Model	**Assumption**								
A	NSPS in SO_2, TSP	68.851	75.529	5	6	68.830	75.510	16	15
B	NSPS in TSP	68.847	75.528	7	6	68.734	75.422	64	55
C	Conventional Combustion, FGD 1000 μg/10^6 Btu POM[a]	No detectable difference from baseline				68.860	75.541	1	0
C	AFBC, 3000 μg/10^6 Btu POM[a]	68.860	75.541	1	0	68.848	75.538	7	1

[a] Polycyclic Organic Material.

many categories and treats only income among the socioeconomic variables. Model C uses pollution estimates that are in some ways cruder than those of Model A, and treats no socioeconomic variables at all, but it is the only model to consider smoking as a complicating factor. It has the additional disadvantage that it was derived from the fusion of two independent and unrelated studies. It is our view that Model B is most likely to give "best" estimates of the magnitude of the quantitative effects.

3.1.3 Extraction and Transportation Health Risks

The following conclusion can be drawn from an analysis of health impacts caused by mining and transportation accidents associated with coal: LSC, for the assumed extraction bv surface mining of western coals, will reduce the number of fatal accidents by a factor of about three compared with FGD and FBC options that use high-sulfur coal from underground mining. However, because of the long transport distances (to the Midwest) for the LSC option, the impact of transportation-related accidents can be expected to be three times that of the other options. The net result is that fatal injuries are about the same for the four options. (Non-fatal injuries for the LSC option are a factor of three below the other options.)

Mining and transportation accidents associated with extraction of the sorbent for sulfur removal also entered the estimation. Because large tonnages are involved, these numbers are visible. For mining, the fatalities are less than ten percent of those for underground coal mining. Transportation fatalities are less than 20 percent of those associated with the transportation of high-sulfur coal. The conclusion is that the health impacts associated with the sorbent extraction and transportation are much less important than those from coal extraction and transportation.

Impacts from the disposal of the ash and spent sorbent, if deposited offsite, will depend on the distance hauled. The economic incentive to move these wastes significant distances will probably not be present. Impacts from the fresh sorbent are small; therefore, those from the disposal of spent sorbent and ash will also be small.

About two accidental deaths per year are expected in the total coal supply activity for a 1000-MW plant serving a Midwest market, from either underground or western surface mining.

Another area of impact involves the health effects due to mining--in particular, risks undertaken by coal miners. Underground mining of coal has contributed to excess disabilities and to premature death from pulmonary disease. For working conditions in the past, permanent disability among miners due to pulmonary impacts was about 3/1000 MWe-yr for a coal-burning plant. Milder disabilities might be three to six times greater. Working conditions have changed, and new health and safety standards are being met in the mines. Impacts from future mining of coal--starting after 1985--are difficult to estimate. Perhaps a reasonable guess of the upper limit of permanent disability for 1985 mining is 10 percent of the above historic rate. If one considers a permanent disability to be comparable to an accidental death, then the guessed-at rate would be less than one-third of the accidental death rate in an underground mine.

3.1.4 Summation of Health Impacts

Among the four options, no particular combustion technology appears to have an advantage for the health impacts examined. Transportation impacts are important for surface mining; and accidental deaths, for underground mining. Other health impacts due to sorbent and ash are small compared with total coal-transportation and mining accidents for a high-sulfur coal system or for accidents from low-sulfur western coal used in the Midwest. The public health risks from generating-plant emissions are similar among options with similar siting and cause considerably more excess deaths than the accidents in coal mining and transportation. The contribution of miner pulmonary disability is uncertain, but expected to be a small part of total health impacts by 1985.

Public health risks, such as illness, due to the energy system were not quantified. The health impacts here are associated with increased mortality.

3.2 ENVIRONMENTAL IMPACTS

Because all types of combustion under consideration will be required to meet the NSPS, there will be very little difference in the potential terrestrial or aquatic ecological impacts of the gaseous atmospheric emissions from a 500-MW unit using any of the four combustion methods, based on process data available to date. PFBC is expected to have the lowest NO_x emissions (and therefore the lowest potential for NO_x ecological impacts), and the lowest particulate emissions, because of the necessity to minimize erosion of the gas turbine blades. Ecological impacts from particulates can result from the potentially toxic trace elements that tend preferentially to condense onto the smallest particulates, which generally escape even the most efficient emission abatement equipment. Although no impacts from trace elements reaching toxic concentrations are anticipated, FGD would emit the most trace elements, followed by LSC, AFBC, and PFBC. This ranking assumes less enrichment of trace elements on the finer fly ash particles from FBC.

The potential for terrestrial or aquatic impacts from hydrocarbon emissions is low, but research is needed on the types and quantities of these hydrocarbons and their effects on the biota to fully assess the potential impact.

The major differences in the ecological impacts of either type of fluidized-bed combustion (AFBC or PFBC) versus conventional combustion (FGD or LSC) are associated with the disposal of solid wastes. These can be summarized as follows:

1. <u>Desulfurization Waste</u> - The quantities of desulfurization waste generated by FGD, AFBC, and PFBC are of the same order of magnitude, but differences in the physical characteristics of the wastes, and the high content of calcium sulfite (on the order of 65%) in FGD waste, lead to significant differences in the environmental effects of waste disposal. The sulfite content of the sludge will greatly increase the oxygen demand of surface waters receiving settling pond effluent or seepage, with severe adverse effects to the environment.

For FBC, the material is dry and of relatively low toxicity, and with adequate R&D the possibilities seem good for spent sorbent utilization and/or ultimate disposal and reclamation of the disposal site. Sludge-settling ponds are required only for FGD; due to the thixotropic nature of the sludge, dewatering to less than 50 percent moisture is difficult, and land areas will be continually needed as settling ponds for the life of the station unless effective fixatives and/or disposal techniques are developed that will overcome those characteristics of the sludge that render it unsuitable for landfill or reclamation.

2. Ash - All four technologies will generate ash, collected by emission-abatement equipment and/or accumulated as bottom ash and slag. The characteristics and quantities of the ash will vary among the technologies, and will also depend on the characteristics of the particular coal burned and on operating conditions; in general, however these differences are not so marked as to allow one technology to be rated higher than the others in terms of waste disposal. The ash is dewatered or slurried to settling ponds, allowed to dry, and transported to an ultimate disposal site (a small percentage is utilized as fertilizer, road-building materials, etc.). Environmental impacts of the ash occur through the seepage and leaching from settling ponds or disposal sites of such elements as Se, B, Zn, Cu, As, Cd, Be, and Cr, which are potentially toxic to vegetation, foraging animals, aquatic life, and man.

For those parameters assessed in this report (SO_x, NO_x, trace elements, hydrocarbons, and solid wastes), the potential impacts of PFBC and LSC are more environmentally acceptable than FGD or AFBC, on the basis of currently available data. PFBC has fewer NO_x and particulate emissions than AFBC, FGD, and LSC. LSC has the lowest amounts of solid waste to dispose of and fewer hydrocarbon emissions than FBC. The waste materials from FGD are more difficult to handle, and FGD has the highest quantities of trace element emissions.

Environmental impacts for mining, cleaning, and transportation of coal were not evaluated. Differential quantification of these factors depends not only on the general location of the coal source, but also on the specific coal quality and mining operation. For FGD-versus-AFBC alternatives there would be no practical difference in these environmental impacts because each would use high-sulfur coal from the same source.

3.3 SOCIETAL IMPACTS

To the extent that FBC would displace the use of western low-sulfur coal in the Midwest, this technology could provide some social benefits. Its use would lessen the social disruption resulting from coal resource exploitation in the rural West and would cause less social disruption in Midwest and Eastern applications through use of a social and institutional infrastructure more capable of dealing with growth in the coal industry.

3.4 RESOURCE USE

There are not great differences in resource use among the systems. The major problem is the disposal of spent sorbent from the FGD, AFBC, and PFBC, which affects land use and environmental quality. The impacts related to resource use are summarized below.

3.4.1 Energy Resources

Heat rates for the AFBC, PFBC (introductory version), and LSC are within five percent of that for FGD. Ancillary energy required for sorbent production or capital equipment construction is a minor difference, so the lifetime net energy produced by each system depends primarily on heat rate. The systems using high-sulfur coal allow use of more abundant coal resources.

3.4.2 Materials Resources

Sorbent requirements for a 500-MWe plant of 135, 350, and 290 thousand tons per year for FGD, AFBC, and PFBC, respectively, should pose no major problems of availability. Other materials use by the systems is comparable, except possibly for small amounts of critical materials, such as chromium or cobalt, for the PFBC gas turbine.

3.4.3 Basic Natural Resources

Land requirements differ due to problems of sorbent disposal, which are largely unresolved. Water requirements differ only due to heat rate, assuming wet cooling towers for all systems. Air quality will be determined by local conditions and system emissions; FBC systems emit more hydrocarbons, but PFBC has lowest NO_x and particulate emissions.

3.4.4 Economic and Manpower Resources

The LSC power plant is some \$100/kW cheaper (1975 dollars) than FGD, AFBC, and PFBC. Construction manpower needs are about the same for the alternatives. FGD requires about 20 percent additional manpower for plant operation over the LSC plant. AFBC and PFBC would require slightly greater operational manpower than the LSC plant.

3.5 DOLLAR COST

The costs of electrical energy from the various alternatives were estimated in order to broaden the perspective of the assessment. These estimates were largely based on work by others. In addition to the usual difficulties in estimating costs, regional aspects of coal supply and compliance with the various state standards complicate an interpretation.

The assessment is directed toward new electrical-energy conversion facilities to supply the base-load portion of customers' demand. In general, fluidized-bed facilities would not be constructed as replacements for existing boilers. Because the capital costs for FGD and FBC are higher than for LSC, these will have a tendency to be selected for base-load operation; the LSC option will be preferred for supplying the intermediate electrical loads.

Costs were not estimated for all regions in the U.S. One regional estimate was made for a central Illinois plant burning either western low-sulfur or Illinois high-sulfur coal. The electrical energy costs in 1975 dollars are expected to fall into the following ranges for facilities having a 65 percent annual capacity factor and 18 percent annual charge rate:

	mills/kWh
LSC (western low-sulfur coal)	29-25
FGD (high-sulfur coal)	31-27
AFBC (high-sulfur coal)	33-26

For other regions close to high-sulfur coal, the FGD and AFBC costs would probably fall in the same range. The LSC option using western low-sulfur coal would increase for plants east of Illinois.

In an estimate made for the PFBC technology, the electrical energy cost has the same range as for the AFBC. These cost estimates do not include any special provision for disposal of the spent sorbent waste from the FGD or AFBC alternatives. It is believed that the cost for fixing the sludge from the FGD to greatly reduce leachability and to provide some strength for bearing loads would be in the range of 0.5 to 1.0 mill/kWh. The preparation of the spent sorbent wastes from AFBC to increase disposability should be lower than for FGD sludge.

4. SUPPORTING MATERIAL

Preceding sections of the report have reported conclusions of the Task Force members regarding the key technical features and health/environmental impacts of the four technology options under consideration. Section 4 presents details of the data analyzed by the team in making the foregoing assessments, and can be read in conjunction with the earlier chapters. The supporting materials on Health Effects (4.1), Environmental Effects (4.2), Societal Impacts (4.3), Resource Use (4.4), and Costs (4.5) parallel the discussion of these topics in Section 3. The Technical Description (4.6) and Summation of Current R&D (4.7) parallel Section 2. The approach in this section is therefore the same as in the previous material: the reference unit remains a 500-MWe plant; the approach is comparative; the details represent the experience of the Task Force and/or current literature. The scope of the discussion broadens to include the range of effects possible for those most and least susceptible to impact by coal combustion technology.

4.1 HEALTH EFFECTS

4.1.1 Health Impacts in General

The principal effluents from current modes of coal utilization that directly affect human health occur in the stack emissions from coal-burning facilities and appear as airborne pollutants. Four major impacts result: physiological irritation, direct toxicity, carcinogenesis, and metabolic or physical synergism.

The body's response to the pollutant may cause an inflammatory reaction, characteristically seen as a local reaction. This defense mechanism, physiological irritation, helps the body reject foreign materials.

Direct toxicity results when an agent interfers with normal cell metabolism, by inactivating key enzymes, being metabolized into useless products, etc. In general, substances with toxic effects will also stimulate inflammation, but the response is not always proportional to the dosage. Inflammation usually occurs at the site of contact, whereas toxic effects may show up anywhere in the body after a substance is absorbed.

The pollutant and/or its metabolic by-products may induce the development of carcinogenic tumors after a latency period that can range from a few years to several decades. This may occur as the result of an accumulation of gene mutations or chromosome aberrations due to biochemical reactions between the genetic material of the cell and the carcinogen.

In the respiratory system in particular, there is a further, synergistic class of effects. Although not directly harmful in and of themselves, some substances are capable of potentiating the effects described above. For example, the mechanisms for clearing noxious substances from the lungs may be reduced in effectiveness by one agent, thereby increasing the residence time of other effluents in the lung. This may result either from a reduction in the ciliary action in the bronchial tree that moves foreign particles out of the lungs or from a thickening of the protective layer of mucus over the celia, which interferes with ciliary action.

The body's response to these impacts may differ according to the age and condition of the victim, the nature of the noxious agent, and the duration of exposure. The clinical manifestations typically observed among persons exposed to airborne pollutants derived from coal combustion involve pulmonary and neoplastic disorders.

Inflammation of the pulmonary tissue and the general debility produced by toxic effects make both the upper and lower respiratory tracts more subject to infection. Thus, the incidence of colds, influenza, pneumonia, and acute pulmonary diseases tends to be elevated in exposed populations. Acute asthma attacks can be induced in susceptible persons by respired irritants, and the severity of an attack, whether pollutant-induced or not, can be markedly increased by the synergistic relationships found between the body's response to histamines (released in the initial phase of an asthma attack) and prior exposure to other irritants.

Early inflammatory responses have been shown to lead to the development of various pneumonoconioses (silicosis, asbestosis, etc.) when certain kinds of irritant particles are introduced. A person already in poor health from a condition such as chronic respiratory or cardiovascular disease, whether originally caused by the pollutants in question or not, is at much higher risk of suffering an acute or fatal episode when exposed to airborne irritants. Prolonged exposure to irritants and toxins has been shown to lead to irreversible damage to lung tissue. Emphysema and chronic bronchitis have been shown to develop in a variety of experimental animals exposed to low levels of common pollutants. (These are also characteristic effects of chronic pulmonary injury seen, for example, after prolonged use of tobacco.)

Exposure to carcinogens of the kinds found among coal combustion products can lead to neoplasia or cancer in the site or organ of deposition. However, metabolic transport and transformation has the potential for causing cancer in other organs as well.

4.1.2 Health Effects Associated with Specific Pollutants

4.1.2.1 Sulfur Dioxide

Sulfur dioxide (SO_2) was one of the earliest suspected toxic agents in air pollution episodes, and has therefore been studied extensively. In the pure state, it is a colorless gas with a slight acrid odor. In high concentrations, it is generally absorbed in the upper respiratory tract and never reaches the pulmonary region; but at low concentrations, most of the inhaled amount reaches the terminal bronchioles and alveoli. Thus, the effective dose received by the most sensitive parts of the respiratory system does not decrease linearly with decreasing atmospheric concentration. In the pure state, SO_2 has not been shown to produce serious direct effects to humans for those concentrations ordinarily expected in areas of heavy coal utilization (0.3 to

1.5 ppm), although levels above 0.25 ppm are usually associated with adverse health effects in epidemiological studies.[1]

In humans, initial exposure at levels that might be realistically encountered produces a slight temporary vasoconstriction which lasts about 10 to 20 minutes in a previously unexposed subject, with measurable reduction in the elasticity of the lung lasting for somewhat longer periods of time. Subjects exposed over several days show slight changes in lung capacity and pulmonary resistance, levels of various enzymes, and blood chemistry. There appears to be a habituation effect, i.e., a person with previous exposure to low levels of SO_2 does not react as severely to a given higher dose as an unexposed person. In the worst-case realistic dose range, the irritant effect is mild, and tends to decrease with habituation. Long-term, low-level doses result in the thickening of the mucus layer over the cilia, producing, in the long run, an effect similar to that seen following acute exposure.[1]

SO_2 has been found in some studies to interact with other irritants, both enhancing and ameliorating their effects. An experimental subject habituated to SO_2, for example, will not react as strongly to a subsequent dose of nitrogen dioxide as one without prior exposure. Indications of a synergism have been found in studies involving ozone (O_3) and histamine; previous exposure to SO_2 will result in more severe reactions to those irritants.

4.1.2.2 Nitrogen Oxides

Nitrogen oxides (NO_x) are produced by the oxidation of organically bound nitrogen in coal and by the secondary oxidation of atmospheric nitrogen during the combustion of coal and most other hydrocarbons, especially at high temperatures and/or pressures. The two most important species are nitric oxide (NO) and nitrogen dioxide (NO_2, also known as nitrogen peroxide). Nitrogen oxides are also important in the generation and regulation of O_3 levels and in producing the organic components of photochemical smog. The species most commonly found in the atmosphere is NO_2.

NO_2 is a strong irritant. Rats experimentally exposed to as little as 0.5 ppm show signs of acute inflammatory response after only four hours of exposure. Chronic exposure of experimental animals to levels insufficient to produce evidence of acute inflammation produced irreversible emphysema-like lesions. Human experiments at moderate levels have shown evidence of inflammation as measured by diminished lung compliance, but unlike the effects of SO_2, this reaction seems to be delayed several hours after the onset of exposure. As with SO_2 and O_3, there is a protective habituation effect to the effects of acute inflammation. This protection does not necessarily apply to effects other than acute inflammation. In fact, in the opinion of many researchers the reverse is true: the mechanism of habituation to the acute inflammatory response may be part of the effect of chronic toxicity. NO_2 seems to reduce ciliary action in the same fashion as SO_2.

4.1.2.3 Carbon Monoxide

Carbon monoxide (CO) may be produced during incomplete combustion of coal, and is therefore most likely to appear when a concerted effort is being made to control NO_x emissions. CO is best known for its affinity to hemaglobin--combining to form carboxyhemaglobin (COHb), which has a very long residence time in the blood. At COHb blood levels greater than 1.3 percent over eight hours, persons with stable coronary artery disease (angina pectoris) may begin to note increased frequency and duration of symptoms; at blood levels of 1.9 percent, excess deaths may occur among people with pre-existing cardiovascular disease.[2]

4.1.2.4 Hydrocarbons and Photochemical Products

Coal has no fixed structure; it is generally viewed as a network of aromatic carbon compounds interspersed with various heterocyclic compounds. The potential therefore exists for the formation of a wide variety of organic effluents, especially during transient operating conditions which permit incomplete combustion.

The consequences of hydrocarbon inhalation are complex because the inhaled substances are always in mixtures. This intermingling of compounds makes it virtually impossible in field studies to incriminate any single material as the agent in the causation of pathologic changes. However, in experimental situations a number of organic compounds arising from the combustion or processing of coal have been identified as either known or "suspect" carcinogens, others as strong eye and lung irritants.

The products of incomplete coal combustion include aliphatic and aromatic hydrocarbons, aldehydes, and ketones. Of the aldehydes, formaldehyde and acrolein are recognized as the two most common hydrocarbon irritants. These compounds are easily absorbed across the mucous membranes of the conjunctivae and alveoli. Their initial actions are to produce tears (lacrimation) or sneezing (sternutation).[3] Effects associated with inhalation include rhinorrhea, cough, sore throat, and a sense of substernal oppression. Irritation from formaldehyde is apparent to most people at concentrations of 2 to 3 ppm; the same reactions from acrolein, at less than 1 ppm.[4]

The intensity of acute and chronic inflammatory reactions will depend on the specific toxicological properties of the pollutant. Olefins or unsaturated aldehydes produce more noticeable irritation than saturated aldehydes. Their toxicity increases with the addition of a double bond and decreases with increasing molecular weight.

The water solubility of a hydrocarbon pollutant will determine where it is absorbed in the respiratory tract. Highly water-soluble products tend to be absorbed in the nasal, buccal, nasopharyngeal, and laryngotracheal regions. The higher-molecular-weight, less soluble compounds are able to penetrate into the alveoli and terminal airways.

The products of coal combustion having the most serious potential for carcinogenic effects are the polycyclic compounds. Polycyclic aromatics and aza-arenes derived from the benz(a)anthracene skeleton, have been shown to contain a number of strong carcinogenic agents.[5] The most widely studied is benz(a)pyrene,[6] which has been clearly established as a causative factor in skin and lung cancers among experimental animals.

Photochemical reaction products, resulting from the interaction of combustion products with ultraviolet radiation and the oxidation of effluent hydrocarbons, can be considered as secondary products of coal combustion. Ozone and the PAN series are examples of this group. Photooxidation is also a pathway for aldehyde formation.[4] The PAN series--peroxyacetyl nitrate (PAN), peroxybenzoyl nitrate (PBzN), and their homologues--are potentially more toxic than the aldehydes. However, due to their high reactivity and short lifetimes, the extent to which the PANs are directly responsible for irritant effects is questionable.

4.1.2.5 Particulates and Trace Elements

A significant portion of coal combustion products are the microscopic solid particles and liquid droplets, termed particulates, formed during and after combustion. Although the size range given for atmospheric particulates extends from 0.005 to 500 micrometers, the particulate matter from coal combustion appears in a more limited size range (in the 0.01 to 10 micrometer range of equivalent aerodynamic diameters). Because this range neatly brackets the size defined for respirable particles, these particulates pose a significant potential for adverse human health effects.

Mechanical procedures can reduce the size of the coal itself or its ash to particles on the order of several micrometers in diameter. During combustion, coal constituents can vaporize and later condense, or a fine ash with particles of 0.1 to 1 micrometer can be produced. Partial combustion can form soot particles 0.01 to 1 micrometer in diameter. The energy available from combustion can also be responsible for the formation of condensation nuclei 0.01 micrometers in diameter. Direct combustion processes give rise to primary particulates; secondary particulates can be formed from the post-combustion interactions of gaseous products and sunlight. The sulfates, nitrates, and hydrocarbons usually result from photochemical reactions. The size range associated with these particles is 0.01 to 1 micrometer.[7]

Virtually all naturally occurring elements can be found as contaminants in coal. The emission of these constituents is dependent on their chemical form prior to combustion and on their volatility.[8]

Most elements in coal, exclusive of carbon, come in the form of aluminosilicates, inorganic sulfides, and organic complexes. During combustion, the sulfides and organic compounds are decomposed to produce SO_2 and a number of oxides and other chemical species of varying volatility. The aluminosilicates, on the other hand, have very high vaporization temperatures, and tend therefore to survive more or less intact as fly ash and slag.[1]

Many of the elements and compounds which volatilize and adsorb on particulates are known to have adverse effects on human health.[9] When adsorbed on such surfaces, SO_2 is in many cases transformed into SO_3 and sulfate ion far more readily than it is in the gaseous state, and in the presence of high humidity may form aerosols of sulfuric acid or other acid sulfates.

The effects of particulate or particulate-borne emissions on human health are determined by three factors: the composition of the particulates, their size, and the amount of time they spend in contact with sensitive tissues.

The lungs constitute the major route of entry for toxic airborne particulates. The probability of particle deposition and the anatomical site in which deposition occurs is primarily a function of particle size. Particles less than about 0.01 micrometers in diameter tend to behave as gases, and may not be deposited at all. Particles with 0.1 to 1 micrometer diameters are predominantly deposited in the alveolar or pulmonary regions, while large particles show a greater tendency to deposit in the nasopharyngeal and tracheobronchial regions.

The surface of the alveoli must be kept clear of deposited matter to allow for efficient gas exchange. Phagocytosis of insoluble particles or aerosol droplets by alveolar macrophage cells is the principle clearance mechanism of this area. The rate at which particles are cleared from lung areas is variable. For those engulfed by macrophage cells and carried to the ciliated epithelium or lymphatic system, the residence half-life is two to six weeks. If the macrophage does not succeed immediately in clearing it, the foreign particle may become sequestered in the lung. In this case the residence half-life rises to several months or years, and the clearance rate will depend upon particle solubility.

A cytotoxic material can influence its own rate of clearance. Such a substance can damage or destroy the phagocyte, thereby directly reducing macrophage action. Tissue reaction to a sequestered particle can result in the progressive segregation of the foreign body behind a mass of fibrous material, making removal more difficult. The formation of the silicotic nodule is an example of the latter type of reaction.[10]

The toxic effect produced by respirable particles depends on the chemical species contained. Small particles are generally more toxic than large ones.[11] A submicron fly-ash particle presents a double threat to human health. Not only does it reach the pulmonary region of the lung and remain there for extended periods, it also delivers relatively high concentrations of combustion effluents. Because they can adsorb SO_2 and other irritant gases and vapors, respirable particulates have the ability to magnify their initial effects by holding high concentrations of these irritants in close proximity to sensitive tissues for protracted periods.

The sulfate ion, which is often associated with small particles and aerosols, appears to be a far more potent irritant than any of the others discussed here. This is probably due in part to the fact that the ion forms a very strong and reactive acid and also to the fact that it is so strongly associated with the particulates.[1] Cations associated with sulfates are important mediators of irritant potency.[12] Pure sulfuric acid (H_2SO_4) and ferric ammonium sulfate ($FeNH_4[SO_4]_2$) are the most potent forms. Other ions tend to be weaker in proportion to their acidity.

Particulates act as carriers of many trace elements and hydrocarbons in the effluent stream. Nickel (in the form of nickel carbonyl), chromium (especially in the form of chromic trioxide), beryllium, and arsenic have been implicated as carcinogens. Many organic particulates contain the known carcinogen benzo(a)pyrene and related compounds. Lead, tellurium, mercury, arsenic, selenium, cadmium, nickel, chromium, and vanadium are all known to be highly toxic,[13] with many exhibiting a special propensity for cellular deposition and retention. These elements are capable of interfering with and disrupting the function of the central nervous system and other organ systems of the body unrelated to the respiratory system.

4.1.3 Analysis of Health Effects from Airborne Toxic Agents

The first step in the analysis of health effects is to define the source term, in this case the toxic agents entrained in the effluent stream. A variety of coal products are involved: oxides of carbon, sulfur, and nitrogen as gases; volatile organics and inorganics as vapors; and particulates of varied sizes derived from varied sources. These products vary with the type of coal used, the combustion process, and the efficiency and types of pollution-control devices applied. Estimation of dose rates from these airborne effluents requires knowledge of their chemical and physical nature and their interactions with the physical environment into which they are introduced.

With assumptions made from measurement of the effluent stream, and use of appropriate atmospheric transport equations, it is possible to predict the most likely concentration to be inhaled by the exposed population, and therefore to estimate the dose received. Physiological and pathological responses in the population will reflect both the individual's ability to respond and the duration or history of exposure. Some individuals will have severe short-term reactions to any increased level of a contaminant, which will be manifest as an increased incidence of respiratory disease or asthma, aggravation of pre-existing chronic cardio-pulmonary disease, and premature death. Long-term exposure to coal combustion effluents may result in an increased incidence of chronic respiratory diseases and cancer in the total population.

Although the threshold for response to airborne contaminants is not the same for all individuals, the main concern of a population-risk analysis is with the average individual. The existence of high-risk groups, in which many of the observed or expected responses will occur, is an important factor in the analysis. The risk factors of age, pre-existing illness, genetic sensitivity, occupation, and personal habits (such as smoking) identify those hypersusceptible individuals who may exhibit severe responses to air-contamination levels below the threshold level for the majority of the population.

Predictions of health effects can be made through estimating increases in morbidity and mortality rates for selected diseases as a function of estimated dose. Use of mortality statistics are often preferred, due to accessible records and relative ease of analysis. The calculation of premature deaths (those occurring in excess of the average age-specific rate expected for the population) is the health effect measured or predicted as a function of exposure to the specified pollutants.

The final determination of acceptable risk for a pollutant requires an appraisal of the benefits to be gained by the population as a whole against the costs in terms of increased levels of poor health that may be levied only upon certain members of the population. The high-risk groups identified above can be expected to express the major portion of the illnesses associated with the increased presence of airborne contaminants. The establishment of acceptable levels of risk in such a situation requires the evaluation of many economic, social, and political forces, and is therefore not an integral part of the health assessment procedure.

4.1.4 Limitations of the Analysis

The complex nature of the questions under consideration requires the development of many assumptions that may not be rigorously defensible. Therefore, any evaluation takes the form of a crude estimate rather than a precise determination of specific health effects.

The source term is often poorly defined. Measurement of hot flue gases and particulates must suffice for source measurements, although we recognize that the important reactions that combustion products undergo may not take place until the constituents have exited from the stack and returned to atmospheric temperatures. Atmospheric reaction rates are uncertain and are generally given as the percent of initial constituent converted per hour. This estimate can then be applied to a dispersion model that assumes uniform geography and particle size in order to calculate ambient concentration for the exposed population. A physiological response is then postulated from dose-response estimates.

Some of the dose-response data recorded for man are the result of industrial exposures or experimental studies on humans and animals. The extension of these data to the general population assumes that the population characteristics are not significantly different from those of the work force or experimental population. It is also assumed that chronic low-level exposure will induce responses similar to those from an acute exposure.

Epidemiological studies concerning effects of urban residence and industrialization on health have demonstrated that air pollution is clearly a health hazard; however, there has been only limited success in identifying the causative agents that induce the increased respiratory diseases observed in urban populations. Toxicological experiments have successfully determined dose/response relations for individual constituents of urban air, but those relations are of limited value in predicting the response of an exposed population, as morbidity and mortality result from the interaction of a number of agents rather than only one.

4.1.5 Mortality Projection Models

Until the precise mechanisms of air pollution-induced injuries are defined, measurements associating health effects and ambient pollution levels will depend on general population epidemiological studies. These studies have become the basis for dose-response relationships between some index of pollution and population mortality. The mortality projection models employed for this analysis insert the dose-response data into a demographic model that can address underlying forces of mortality and predict increments of excess risk in a manner not biased by time-dependent age distribution effects.

Three independently derived models, based on different index pollutants, are used for this analysis. The first model is taken from Lave and Seskin and reported by Finch and Morris (Model A).[14] This model relates total mortality to two independent pollutants measured simultaneously: sulfate ion ($\mu g/m^3$ $SO_4^=$) and total suspended particulates ($\mu g/m^3$ TSP). Model B is based on data from Winkelstein's study of mortality related to total suspended particles (TSP) in Buffalo, New York, also analyzed by Morris.[14] Model C, based on data analyzed by Carnow and Meier,[15] associates the pollution index of benzo(a)pyrene ($\mu g/m^3$, BAP) with lung cancer mortality. With appropriate adjustments, this index can be related to total mortality as well. These adjustments include a regression equation derived by Larson and Clements[15] using state-level data on BAP concentrations and pulmonary cancer. BAP concentrations were scaled into cigarette equivalents by a comparison with data in Hammond's study.[16]

The projection models all take the form of 'absolute risk'. They take an input mortality schedule of sex and age-specific death rates (${}_n^sM_x$) and project the rates to be expected under the increment of pollution with a simple linear equation of the form

$${}_n^sM_x^* = {}_n^sM_x + B_iP_i + \ldots + B_kP_k$$

where P_i is the increment in ambient pollutant concentration ($\mu g/m^3$) to be expected and B_i is the slope of a regression line defining the effect pollutant 'i' will have on mortality. Width of age group, beginning age, and sex are specified by n, x, and s. Table 4.1 gives the regression coefficients of each model.

4.1.6 Applicability of Models

The appropriate measurement of public health impacts for comparative purposes depends on the comparison intended. We have calculated two measures: the expectation of life (e_0), which is the expected life span of an individual exposed for life to the pollution considered, and the change in the annual death rate per million population that would be observed over a 25-year period with the same initial population (Table 4.2).

Table 4.1. Mortality Projection Model Regression Coefficients (B)[a]

Model and Population	Age Group	Sex	Probability of Death, $\mu g/m^3$ Dose Rate		
			B_{TSP}	B_{SO_4}	B_{BAP}
Model A	15-44	M	2.5×10^{-7}	0	-
		F	6.0×10^{-7}	4.0×10^{-7}	-
	45-64	M	1.19×10^{-5}	1.15×10^{-7}	-
		F	5.5×10^{-6}	7.2×10^{-6}	-
	65+	M	0	7.82×10^{-5}	-
		F	0	6.36×10^{-5}	-
Model B	15-44	M	2.0×10^{-6}	-	-
		F	3.0×10^{-6}	-	-
	45-69	M	1.4×10^{-4}	-	-
		F	7.0×10^{-5}	-	-
	70+	M	5.6×10^{-4}	-	-
		F	4.0×10^{-4}	-	-
Model C	35-54	M	-	-	0.300
		F	-	-	0.046
	55-64	M	-	-	0.758
		F	-	-	0.717
	65-74	M	-	-	1.215
		F	-	-	0.187
	75+	M	-	-	2.378
		F	-	-	0.366

[a] These models should be regarded as provisional; they are under active reevaluation, and later values may differ significantly from those given here.

For many pollutants, there exist emission standards that must be met by all new power plants irrespective of the technology employed. Analytical Models A and B are both based on pollutants thus regulated, so there is little to be gained by comparing combustion methods for these pollutants. We therefore present here only general results for a hypothetical 1000-MWe power plant meeting the indicated standards. For hydrocarbons, however, there are no NSPS or other regulations, so we present results comparing AFBC with conventional combustion and flue gas desulfurization (FGD).

The pollutant plume does not spread evenly over the area of impact, defined for purposes of analysis as a circle with a radius of 50 miles centered around the point source. Our results are therefore divided into two parts. The first part is calculated on the assumption that the population is

Table 4.2. Results From Public-Health Impact Analysis for a 1000-MWe Plant

		Average Values for 50-mile-radius Circle				Highly Impacted Subarea			
		Expectation of life (e_o)		Deaths/10^6		e_o		Deaths/10^6	
		M	F	M	F	M	F	M	F
Baseline Values (Berkshire Co., Mass., White Population, 1970)		68.861	75.541	11,583	10,705	Same			
Model	Assumption								
A	NSPS in SO_2, TSP	68.851	75.529	5	6	68.830	75.510	16	15
B	NSPS in TSP	68.847	75.528	7	6	68.734	75.422	64	55
C	Conventional Combustion, FGD 1000 μg/10^6 Btu POM*	No detectable difference from baseline				68.860	75.541	1	0
C	AFBC, 3000 μg/10^6 Btu POM[a]	68.860	75.541	1	0	68.848	75.538	7	1

*Polycyclic Organic Material.

distributed evenly throughout the impact area, and that the mean exposure is the mean concentration to be found in the area. The second part is calculated on the assumption that the entire population lives in the part of the study area which contains the higher concentrations of pollution, and can therefore be taken as something of an "upper limit" to the effects discussed. Such areas, it should be noted, are characteristically valleys or other flat areas surrounded in part by physical barriers to air movement, and are therefore also likely to be places considered desirable as locations for human activities.

The models used here all have disadvantages and peculiarities which should be mentioned. Model A was derived from data combining reasonable measurements of complicating social and economic factors, but very poor estimates of actual population exposures to the pollutants studied. It can therefore be expected on statistical grounds to underestimate the relative importance of pollution variables. Model B is based on a study which was able to get reasonable measures of pollution exposure, but which suffers from small-number problems in many categories and treats only income among the socioeconomic variables. Model C uses pollution estimates that are in some ways cruder than those of Model A, and treats no socioeconomic variables at all, but it is the only model to consider smoking as a complicating factor. It has the additional disadvantage that it was derived from the fusion of two independent and unrelated studies. It is our view that Model B presently provides the "best" estimates of the magnitude of the quantitative effects.

4.1.7 Transportation and Extraction Impacts

The extraction and transportation health risks broadly depend on the method of mining (surface or underground) and on the distance of the power plant from the mine. Details of the mining operation and how the coal is transported are also important. For coal, we shall consider health effects due to accidents and to pulmonary disabilities. In addition, because of the large amount of sorbent used in the FGD and FBC plants, health effects due to accidents in quarrying and hauling this material will be estimated.

The basis for and the results of the accident analysis for coal mining and transportation are given in Table 4.3. The total fatal accidents for FGD, AFBC, and PFBC are about the same. The LSC alternative, which uses western low-sulfur coal, shows a lower number of fatalities in the mining activity but a higher number of transportation fatalities. The fatality estimate is based in unit trains, but the fatality rate per train is based on the U. S. average freight train accidents; the number may not represent what will occur in the future due to coal train operation in the West and improved railroad crossing protectors. Also, in place of the 600 miles distance, 750 miles might be used. Because of the uncertainty in future accident rates, a reasonable assumption is that the fatality rates for mining and transportation are equal for Midwestern plants using western low-sulfur or midwest high-sulfur coal.

Table 4.3. Accident Analysis, Coal Mining and Transportation

	Basis, 1000 MWe-yr (100% Capacity)							
	LSC		FGD		AFBC		PFBC	
	F[b]	NF[c]	F	NF	F	NF	F	NF
Extraction								
Underground (Coal)			1	96	1	99	1	93
Surface (Coal)	0.3	15						
Quarry (Limestone)			<0.1	1	<0.1	2	<0.1	2
Transportation								
Coal	2.0	22	0.6	7	0.6	6	0.5	6
Limestone or Dolomite	—	—	0.1	1	0.1	1	0.1	1
TOTAL	2.3	37	1.8	105	1.8	108	1.7	103

[a] Bases for the accident analysis:
low-sulfur western coal: one-way distance 600 miles
high-sulfur region coal: one-way distance 200 miles
limestone and dolomite: one-way distance 100 miles

[b] F = fatalities

[c] NF = non-fatal injuries

The table also provides some information on the fatalities for mining limestone or dolomite. It is readily appreciated that this source of impacts is small and overshadowed by coal mining accidents. The transportation accidents for the material are also small. With these accidents making a small contribution, the transportation of wastes off-site would be expected to be small for nominal distances. Trucks could be used for transporting spent material; the fatal-accident rate per ton-mile could be significantly higher than the rail accident rate, depending on local traffic conditions. Nevertheless, because of short distances, the transportation fatalities in the disposal of wastes are expected to be noticeably smaller than those due to mining and transport of coal.

Another type of concern involves health impacts to the coal miners. Pulmonary disease is a significant source of disability resulting from underground mining of coal. There are various categories of coal workers pneumoconiosis (CWP), and to associate disability with these categories is complex. Based on historical information on CWP, the incidence of disability would range from 2 to 20 per 1000 MWe-year, depending on the classification of disability. According to Sagan,[17] the incidence was about three total disabilities for a 1000-MWe plant operating for one year. The new mining techniques and dust standards are expected to curtail this disease significantly. British experience at 2 mg/m^3 of dust in the mines would indicate no cases of "complicated" CWP and only three percent of the miners would get a mild form of "simple" CWP after 35 years of mining. Mining conditions are not, of course, the same in Britain as in the U. S. Our standards are 2 mg/m^3 of respirable dust in mines.

About 1000 miners are required to produce coal to fuel a 1000-MW plant for a year. On the basis of the British data there might be only one case of simple CWP assignable to the plant. There will be a transition from the historic disability rate to a lower rate as new employees enter the labor force under improved mining conditions. By 1985 the disability rate may be less than 10% of the historic rates.[18] One can say that impacts from permanent disability to miners during the mining period for FBC plants are expected to be low, but some lesser disabilities would occur. Thus, this impact would not appear to be large in the comparison of options.

References for Section 4.1

1. M. O. Amdur, "Air Pollutants." In: J. J. Casarett and J. D. Doull, eds., Toxicology: The Basic Science of Poisons, Macmillan, New York, 1975.

2. A. J. Hackney, "Relationship Between Air Pollution and Cardiovascular Diseases: A Review." In: A. J. Finkel and W. C. Dues, eds., Clinical Implications of Air Pollution Research, AMA Air Pollution Medical Research Conference, December 5-6, 1976, Publishing Sciences Group, Acton, MA, 1976.

3. R. I. Henkin, "Effects of Vapor Phase Pollutants on Nervous Systems and Sensory Function: A Review." In: A. J. Finkel and W. C. Dues, eds., op. cit.

4. Vapor Phase Organic Pollutants, NAS/NRC Committee on Biological Effects of Atmospheric Pollutants, NAS, Washington, D. C., 1976.

5. R. I. Freudenthal et al., Carcinogenic Potential of Coal and Coal Conversion Products. A Battelle Energy Report, Battelle Columbus Laboratories. Columbus, February 1975.

6. Particulate Polycyclic Organic Matter, NAS/NRC Committee on Biological Effects of Atmospheric Pollutants, NAS, Washington, D. C., 1976.

7. P. F. Fennelly, "The Origin and Influence of Airborne Particulates," Amer. Scientist 64:46-56 (Jan.-Feb. 1976).

8. D. H. Klein et al., "Pathways of Thirty-seven Trace Elements Through Coal-Fired Power Plants," Environ. Sci. Technol. 9:973-979 (October 1975).

9. P. F. S. Natusch and J. R. Wallace, "Toxic Trace Elements: Preferential Concentration in Respirable Particles," Science 183:202-204 (January 18, 1974).

10. L. J. Casarett and J. D. Doull, eds., Toxicology: The Basic Science of Poisons, Macmillan, New York, 1975.

11. P. F. S. Natusch and J. R. Wallace, "Urban Aerosol Toxicity: The Influences of Particle Size," Science 186:695-699 (November 22, 1974).

12. M. O. Amdur, "Aerosols Formed by Oxidation of Sulfur Dioxide," Arch. Environ. Health 23:459-468 (December 1971).

13. J. J. Dulka and T. H. Risby, "Ultratrace Metals in Some Environmental and Biological Systems," Anal. Chem. 48:640A-656A (July 1976).

14. S. J. Finch and S. C. Morris, Consistency of Reported Health Effects of Air Pollution, Brookhaven National Laboratory, BNL-218081.

15. B. W. Carnow and P. Meier, "Air Pollution and Pulmonary Cancer," Arch. Environ. Health 27:207-218 (September 1973).

16. F. C. Hammond, "Smoking in Relation to the Death Rate of One Million Men and Women," NCI Monograph 19:127-204 (January 1966).

17. L. A. Sagan, "Health Costs Associated with Mining, Transport, and Combustion of Coal in the Steam-Electric Industry," Nature 250:107-111 (July 12, 1974).

18. W. A. Buckring, "A Model of Environmental Impacts From Electrical Generation in Wisconsin," pp. 140-145. PhD Thesis, University of Wisconsin, 1975.

4.2 ENVIRONMENTAL EFFECTS

4.2.1 Primary Gaseous Pollutant Emissions (SO_x, NO_x)

Conventional coal combustion systems with wet-limestone scrubbing (FGD), and both types of FBC systems, achieve a nominal sulfur-removal value of about 90 percent. The SO_x concentration in effluents from LSC boilers is determined by the sulfur content of the coal. If we assume that an identical coal type will be burned in FGD, AFBC, and PFBC units, the amount of SO_x released to the atmosphere from the three types of units will be practically identical. The average NO_x emissions from FGD, AFBC, and LSC (350 ppm) are similar to and higher than those from PFBC (225 ppm). Data indicate we can further assume that all four types of units could have identical stack heights, identical exit gas temperatures, and just meet emission standards. Under these conditions the dispersion characteristics of the SO_x and NO_x effluents would be quite similar under a given set of meteorological conditions.[1]

The ground-level concentrations of SO_x and NO_x (under typical meteorological conditions) produced by a 500-MW unit of any of the four options, with good engineering design, should be below the level that would cause acute injury even in sensitive terrestrial biota.[1-3] The primary impact on aquatic ecosystems occurs when acidic precipitation formed from these gaseous emissions enters a stream or lake and increases the total acidity above the tolerance level of aquatic biota.[4] This problem is most intense in areas where the natural acid-neutralizing capacity of streams and lakes is very poor, for example the Adirondack Mountain region in New York State.[5] In this region, brook trout populations were lost from lakes severely affected by acidic precipitation.[6]

Such impacts have probably resulted from inadequate stack emission control regulations. However, compliance with the federal New Source Performance Standards (NSPS) will probably lower SO_x and NO_x emissions and adequately control future impacts due to acidic precipitation. Because all new coal-fired generating facilities, regardless of type, will be required to comply with these new regulations, and the regulation will probably provide sufficient protection, it appears that no individual combustion technology has any particular advantage with respect to SO_x- and NO_x-induced impacts to aquatic ecosystems.

4.2.2 Particulate Emissions (Trace Elements)

Certain potentially toxic trace elements tend to condense preferentially onto the smallest particulates, which generally escape even the most efficient emission abatement equipment (electrostatic precipitators). Particulate effluents, subject to atmospheric dispersal, are eventually deposited on vegetation, soil, water bodies, and other surfaces. The effects of trace elements on ecosystems depend on the (1) background concentration, (2) chemical equilibria of the receiving body, (3) chemical form of the element, (4) residence time, (5) sensitivity of the species present, and (6) potential for bioaccumulation in a species or through a food chain.

The following comparative assessment of potential impacts of trace-element emissions from four technology types is based on the assumption that all four can meet the NSPS criterion of 0.1 $lb/10^6$ Btu.

4.2.2.1 FGD-LSC

The assessment of trace-element impacts for FGD and LSC technologies is derived from a previous study that included a worst possible case analysis based on particulate emission dispersal and deposition models for a 1000-MWe power plant utilizing five different coals, and conservative assumptions about trace-element behavior in ecosystems.[1] The previous analysis was limited to 11 elements: As, Ba, Cd, Co, Cr, Hg, Mn, Pb, Se, V, and Zn. Other trace elements would be emitted from use of these two technologies, but were not assessed quantitatively due to the lack of partition factors necessary for the calculation of emissions.[7]

Even when particulate emissions are at the maximum allowed by the NSPS, no adverse impacts on vegetation are expected from the elements studied. The only element estimated to reach marginal toxic concentrations to grazing animals was selenium. Most of the toxicity levels in the literature are based on studies of acute dosage in experimental animals that often have little application to the chronic low-level field exposures associated with pollution sources such as coal combustion.

The potential for enrichment of aquatic ecosystems by a specific trace element from coal combustion emissions appears low. An analysis of trace-element enrichment in hypothetical aquatic systems suggested that dilution prevents the enriched concentrations of selected trace elements from exceeding the water quality criteria and the toxicity threshold of most aquatic organisms. Although the background concentrations of some specific trace elements in surface waters are high in some U. S. streams,[8] no general regional problems were identified with respect to trace-element inputs from a single coal-fired power plant.

Results of an earlier analysis[1] of the effects of trace elements associated with particulates indicate that, on the average, greater quantities of trace elements were introduced into ecosystems from burning high-sulfur eastern coal. Trace-element emissions are expected to be lower for LSC than FGD, assuming that the LSC technology uses western low-sulfur coals, and FGD uses high-sulfur eastern coals.

4.2.2.2 AFBC

The first element in assessing the ecological impact of trace-element emissions from AFBC is the size and composition of the particulates emitted from the stack gases. The process is expected to produce more total particulates than conventional combustion; however, the amount of smaller-size particulates (which normally escape removal by collectors) is expected to be the same. If, as some data suggest, there will be less enrichment of trace elements on the finer fly-ash particles, fewer trace elements would be introduced into ecosystems with this technology. Should this suggestion be incorrect, the trace elements emitted from AFBC would not be expected to exceed amounts emitted from FGD or LSC.

4.2.2.3 PFBC

Trace-element emissions from PFBC will be the lowest of the four technologies if the process requires particulate removal substantially better than the NSPS because of the necessity to minimize erosion of the gas turbine blades. When the technology exists to achieve this reduction in particulates, this process will undoubtedly have the greatest potential for minimizing trace-element impacts to ecosystems. Should the process not require excess particulate removal and NSPS criteria are met, the potential ecological impacts of PFBC would be similar to those of AFBC.

4.2.2.4 Needed Research

This assessment of FBC has assumed that the quantities of trace elements were reduced in the stack emissions. This assumption needs to be verified. Questions to be answered include:

1. Are all elements present in the coal emitted?

2. What are the partitioning factors for the elements?

3. What is the chemical form of the emitted element?

4. Is the deposition pattern of particulates emitted from FBC different from that of conventional combustion?

5. What is the potential for biomagnification of trace elements emitted by coal-fired power plants?

6. How do the various trace elements cycle through an ecosystem or between ecosystems (i.e., pathways)?

4.2.3 Hydrocarbon Emissions

Only very small amounts (relative to SO_x and NO_x) of hydrocarbons would be produced by a 500-MW unit of any of the four types of combustion under consideration.[9] Of particular concern here are the polycyclic hydrocarbons, since some are known carcinogens. There is the possibility, because of the lower combustion/operating temperatures of AFBC and PFBC, that a higher proportion (compared to FGD or LSC) of the hydrocarbons produced by FBC may be of the polycyclic type. The effects of such compounds on other animals or vegetation are practically unknown. However, even the highest short-term hydrocarbon concentrations in the vicinity of a 500-MW unit of any of the four types (considered alone and in terms of direct impact to terrestrial biota other than man) are so low as to be negligible.[1]

Incorporation of hydrocarbon emissions in a hypothetical watershed was done to estimate a worst possible concentration as an indicator of the potential for impacts. This provides some insight into the relative importance of these emissions. Polycyclic organic materials (POM) emissions range from 200 to 1000 $\mu g/10^6$ Btu input for conventional combustion and up to 3000 $\mu g/10^6$ Btu input for FBC boilers. If 2 million tons of coal per year (at 10,000 Btu/lb) were combusted in either type of boiler, and the total annual POM emissions were incorporated directly into a drainage basin with a mean annual discharge capable of supplying sufficient cooling water for a modern coal power plant (ca. 1000 cfs), the resulting POM concentration would range from 0.01 to 0.03 ppb. Because this concentration is quite low and probably would not impact aquatic organisms, there may be no significant difference in POM emission impacts to aquatic ecosystems between conventional and FBC boilers. Although these calculations would suggest an extremely low potential for impacts, research on the type and quantities of POM and other hydrocarbons and their

Table 4.4. Waste Disposal Impacts (Terrestrial) of Four Coal Combustion Technologies

Impacts	Assessment			
	AFBC	PFBC	FGD[a]	LSC[b]
1. Pre-emption of land for settling ponds:				
Ash	4-8 ha/yr	4-8 ha/yr	4-8 ha/yr	2-4 ha/yr
S-removal waste	None	None	8 ha/hr[c]	None
2. Introduction of potentially toxic elements and ions into soil, surface water and ground water by seepage and/or leaching from settling ponds and/or ultimate disposal sites:				
Ash	Yes	Yes	Yes	Yes
S-removal waste	No[d]	No[d]	Yes	NA[e]
3. Ultimate disposal (other than into mine pit) precludes reclamation:				
Ash	No	No	No	No
S-removal waste	No	No	Yes[f]	NA

[a] Assumes wet limestone scrubber.

[b] Assumes Wyoming coal, 6% ash, 1605 ktons coal per year for a 500-MWe station.

[c] Assumes 342 ktons wet sludge per year, with a ponding rate of 1.8 ktons/acre-ft, and a pond depth of 10 feet.

[d] Not applicable.

[e] Equivocal. It is possible that, with R&D, reclamation of sludge disposal sites will be possible; at present, due to the thixotropic nature of the material, utilization as landfill and/or reclamation of disposal site is extremely difficult, except when the sludge is mixed with ash to about 27% moisture and deposited in the abandoned mine pit. See discussion.

Note: The separation of ash from the sulfur-bearing wastes will usually not be complete. In most instances the plant operation will combine the ash with the sulfur wastes for the FGD option. The same procedure is expected for the AFBC and PFBC options.

effect on the biota are needed to fully assess the potential for impacts to aquatic ecosystems.

4.2.4 Solid Waste

Two types of solid waste generated in large quantities by coal combustion are ash and/or desulfurization waste. The characteristics and quantities of the ash (fly ash and bottom ash) produced will vary among the four technologies, and will also depend on the characteristics of the particular coal burned and operating conditions; in general, however, these differences are not so marked as to be major criteria for a policy decision.

Desulfurization waste will result from FGD, AFBC, and PFBC. FGD generates a thixotropic mixture of calcium sulfate (5 to 7%), calcium sulfite (65%), and calcium carbonate (3%), and a moisture content of 50%.[1] AFBC and PFBC generate dry material ("stones") consisting of calcium sulfate; calcium carbonate; calcium oxide; and, in the case of PFBC, magnesium oxide.[10] A number of other constituents make up the balance.* The quantities of desulfurization waste generated by each of the three technologies are of the same order of magnitude--i.e., 291 ktons/yr from AFBC, 315 from PFBC, and 342 (wet) from FGD--but due to differences in the physical characteristics of the wastes and the high calcium sulfite content in FGD waste, disposal is markedly different between FGD and FBC technologies. Differences in the environmental effects of such disposal may well become major factors in policy decisions regarding which technology will be encouraged. These environmental effects are briefly discussed below.

4.2.4.1 Terrestrial Impacts

The impacts of waste disposal on the terrestrial environment are outlined in Table 4.4 for the four technologies. The numbered paragraphs which follow correspond to numbers in the impact column of Table 4.4.

Percentage figures will depend on relative amounts of limestone and/or dolomite (whose $MgCO_3$ content can range from 5 to 95%) used, molar ratio of Ca/S, operating conditions, etc.

1. The land areas used as ash settling ponds for the four technologies are not unreasonably large, and can eventually be reclaimed and turned over to other land usage after the useful life of the station. The reclamation of such areas will not be a simple matter, but the possibilites are good. Of the four technologies, only the FGD requires land area for sludge settling.[11] The potential for pre-emption of this land, with very little change for other usage, is high due to the thixotropic nature of the sludge. Dewatering to less than 50 percent moisture has been extremely difficult unless the sludge is combined with fly ash or treated with a fixative.[12] A number of fixatives are commercially available, but their effectiveness is, to date, not complete. If the power station is a mine-mouth operation, the sludge and fly-ash mixture can be disposed of in the pit; there will usually be sufficient overburden for eventual reclamation of the site. Away from the mine, however, additional land areas will be required on a continual basis for the life of the station.

2. Seepage from ash-settling ponds will add potentially toxic elements and ions to the soil surrounding the pond, and eventually to surface and ground waters. Ash settling ponds are sometimes lined with impervious material, such as clay, before the ash slurry is introduced. This procedure tends to reduce seepage, but will not eliminate it completely; monitor wells would be required to determine the effectiveness of the liner at individual sites. The chemical composition of seepage solution will depend, of course, on the composition of the coal and boiler operating conditions. In addition to ten major chemical constituents in coal ash, there are about 40 so-called trace elements.[13,14] Of these, some (such as B, Mn, Cu, Zn, and Mo) are essential to plant growth but toxic in amounts only slightly higher than their optimum concentrations. Other elements (such as Se, As, Cd, Be, Pb, and Cr) are not known to be essential to the growth of most plants and can, in fact, be toxic to vegetation. These elements can be accumulated in certain species of plants, apparently without harmful effects, but then become toxic to animals which forage upon them. Investigations into the movement of trace elements from sludge and ash pond leachates through soils have concluded that most of the trace elements were removed from the leachates and retained in the soil.[13] This would tend to minimize contamination of groundwater, but would not necessarily prevent eventual uptake of the elements by vegetation in contact with the wetted zone, if the elements were in chemical forms available to

plants. Little is known about the chemical forms of trace elements in coal ash, fly ash, or scrubber sludge, or whether elements initially in forms unavailable to plants would slowly become available due to chemical reactions and/or microbiological action in the soil.

The same concerns apply to the ultimate disposal of fly ash, whether in landfill sites or road-building.[15] Runoff from roads and landfill sites, as well as leaching from the latter, will introduce these elements into other areas. The adverse effects of this impact will probably be evident at the landfill sites, decreasing with increasing distance from the site. Utilization of fly ash as fertilizer can introduce essential nutrients to the soil and enhance crop growth, as long as concentrations in the soil do not exceed the optimum. In certain areas of Wyoming and South Dakota, for example, soils are relatively high in selenium and can produce seleniferous vegetation toxic to grazing animals.[16] Fly ash added to such soils may aggravate the toxicity problem, as fly ash contains high concentrations of selenium.[17] Boron can pose similar toxicity problems.

Disposal of the "stones" from the FBC technologies is expected to have a low potential for trace element toxicity effects.[10] The bulk of the material is, of course, calcium and its salts, but the possibility that trace elements will adsorb onto porous material cannot be excluded. Sulfates are relatively non-toxic to soils, and can, in fact, provide the sulfur requirement of the vegetation. Sulfates are leachable into ground and surface waters, and will add to the "hardness" of those waters. Increasing the "hardness" (calcium sulfates and calcium carbonates) of the water can be beneficial in some respects (lowers Cr^{+++} toxicity)[18] and adverse in others (causes "scaling" of water pipes).

Sludge from FGD contains a high percentage of calcium sulfite. Sulfite discharges to surface and ground waters lowers the oxygen concentration in the water.[19] Oxidation of the sulfite in soils will very likely occur, thus reducing the tendency for adverse effects; effluent from the sludge settling ponds, however, if discharged directly to surface waters, will likely contain adverse concentrations of the sulfite ion.

3. The ultimate disposal of fly ash, whether in the mine pit or in landfill sites, will not preclude eventual reclamation of the areas to productive land use. As mentioned above, reclamation will not be a simple matter but will be possible if adequate attention is paid to depth of overburden and topsoil, seed selection and planting, and maintenance until the area is self-maintaining. Ultimate disposal of FGD sludge, however, may preclude reclamation as currently defined (return of the land to previous or better use), unless procedures can be found to counteract its unfavorable physical properties (see footnote f to Table 4.4). The current best procedure seems to involve mixing with fly ash to about 27 percent moisture disposal in the mine, covering with overburden, and subsequent reclamation. The degree of seepage from the mine site will depend on nature of the substrate and depth to groundwater.

Potential impacts to aquatic ecosystems appear lowest when both fly ash and bottom ash are handled dry and the disposal method consists of ash basins with impervious linings. FBC boilers and conventional boilers burning low-sulfur coal would be advantageous, as they can function without wet-ash handling techniques. However, liquid discharges from wet-ash handling (wet scrubbers and wet sluicing of fly ash and bottom ash) contain significant quantities of toxic trace elements that may affect biota in the aquatic system receiving the overflow drainage from wet-ash basins. Accidental contamination of groundwater from both wet and dry ash deposition basins is possible, and research to find safe uses for the various types of ash is needed.

4.2.4.2 Needed Research

Research is needed to identify:

1. Chemical forms of trace and major elements in fly ash, bottom ash, and slag.

2. Extent of trace-element adsorption onto or within FBC spent sorbent.

3. Effective fixatives for FGD sludge and procedures for dewatering.

4. Effectiveness of settling pond liners.

5. Methods to reduce seepage from ultimate disposal sites.

6. Effects on growth, yield, and trace-element content of vegetation on soils treated with fly ash.

7. Successful reclamation procedures for fly ash and sludge settling ponds.

8. Environmental effects of fly ash utilization in roads and building materials.

4.2.5 Liquid Effluents

Liquid effluents of coal-combustion processes, other than ash pond overflow, would include cooling water blowdown and sewage effluent from the plant site. Because the efficiency of conventional and FBC plants is quite similar, a similar quantity of cooling water would be required for each, and no major differences in impacts to aquatic systems from blowdown would be expected. It is also unlikely that any difference in sewage effluent would exist between the various types of combustion facilities.

From the limited data available on effluent streams from FBC boilers, it would appear that they may have some advantages over conventional boilers with respect to their potential for impacts to aquatic ecosystems. However, considerable research effort is needed to verify this preliminary observation.

References for Section 4.2

1. "The Environmental Effects of Using Coal for Generating Electricity," Nuclear Regulatory Commission, Division of Site Safety and Environmental Analysis, 1977 (in Preparation).
2. "Air Quality Criteria for Nitrogen Oxides," Environmental Protection Agency, Publication AP-84, January 1971.

3. "Effects of Sulfur Oxides in the Air on Vegetation," Revised Chapter 5 for "Air Quality Criteria for Sulfur Oxides," EPA R3-73-030, National Environmental Research Center, September 1973.

4. "Water Quality Criteria for European Freshwater Fish," EIFAC (European Inland Fisheries Advisory Committee) Report on Extreme pH Values and Inland Fisheries, Water Res. 3:593-611 (1969).

5. C. V. Cogbill and G. E. Liken, "Acid Precipitation in the Northeastern United States," Water Resources Res. 10:1133-1137 (1974).

6. C. L. Schofield, "Effects of Acid Precipitation on Fish," Paper presented at the International Conference on the Effects of Acid Precipitation, June 1976, Telemark, Norway (in press).

7. D. H. Klein, A. W. Andren, and N. E. Bolton, "Trace Element Discharges from Coal Combustion for Power Production," Water Air Soil Pollut. 5:71-77 (1975).

8. J. F. Kopp and R. C. Kroner, "Trace Metals in the Waters of the United States," Federal Water Quality Administration, Cincinnati, OH, 1970.

9. "Compilation of Air Pollution Emission Factors," 2nd edition, U. S. Environmental Protection Agency, Publication AP-42, April 1973.

10. "Pressurized Fluidized Bed Combustion Component Test and Integration Unit (CTIU)," System Design Description, Document No. G0219-0052-SA-02, Argonne National Laboratory, December 15, 1976.

11. W. H. Lord, "Disposal of Sludge from Flue Gas Desulfurization," Pol. Eng. pp. 40-41, June 1976.

12. D. M. Carlton and O. W. Hargrove, "Impediments to the Utilization of Flue Gas Desulfurization Systems," Radian Corporation, P.O. Box 9948, Austin, TX, June 1976.

13. W. F. Holland et al., "Environmental Effects of Trace Elements from Ponded Ash and Scrubber Sludge," Report 202, Electric Power Research Institute, Palo Alto, CA, 1975.

14. D. H. Klein et al., "Pathways of Thirty-Seven Trace Elements Through Coal-Fired Power Plant," Environ. Sci. Technol. 9:973-979 (October 1975).

15. N. L. Hecht and D. S. Duvall, "Characterization and Utilization of Municipal and Utility Sludges and Ashes. Vol. III. Utility Coal Ash," EPA-670/2-75-033C, NERC-EPA, May 1975.

16. I. Rosenfield and O. Beath, Selenium, Academic Press, New York, 1964.

17. W. H. Gutemann et al., "Selenium in Fly Ash," Science 191:966-967 (1976).

18. "Toxicity of Power Plant Chemicals to Aquatic Life," WASH-1249, U. S. Atomic Energy Commission, June 1973.

19. H. B. Cooper, "The Ultimate Disposal of Ash and Other Solids from Electric Power Generation." In: Water Management by the Electric Power Industry, Water Resources Symposium No. 8, Center for Research in Water Resources, University of Texas at Austin, 1975.

4.3 SOCIETAL IMPACTS

4.3.1 Scope

The focus of this part of the assessment is on the relative local and regional social impacts that result from the deployment of the coal combustion technologies under consideration. The national societal impacts of a coal-energy economy will not be considered. Specifically, this assessment will describe two types of impacts: (1) regional growth differences and inherent impacts that result from the technology alternatives, and (2) the effects of new technologies on industries and employment.

4.3.2 Regional Growth Impacts

Because of current environmental regulations, LSC and FGD are the options being selected for new coal-fired electrical power plants in most areas of the country. For many regions, the use of western low-sulfur coal meets standards and is the cheapest alternative. (Some regions require FGD in conjunction with the use of this coal.) Boom-town developments and rapid urbanization based upon coal resource exploitation have created serious social problems in rural areas of the West, and projections for future coal needs portend a bleak social picture there.

FGD in plants designed for sulfur coal is another option; coal cleaning to reduce the sulfur content of eastern coal is also being investigated. The FBC alternative (initially atmospheric, then pressurized) will probably find its first markets by displacing some potential uses of the FGD option. Also, for those areas having high-sulfur coal and high transportation costs for low-sulfur western coal, the fluidized bed could be an alternative to the use of low-sulfur western coal. Therefore, FBC is not only a technology alternative but a social alternative as well. Its primary social advantage is a more even geographical distribution of rapid-growth areas, by extending growth to the Midwest, where the social and governmental infrastructures are more developed and therefore more capable of dealing effectively with growth problems. This expansion would also mitigate the socially disruptive migration that is expected to occur with extensive use of low-sulfur western coals.

4.3.3 Effects on Employment

All technology options are expected to utilize similar numbers of construction workers. The operating employment levels for FGD technologies could be slightly higher than FBC because of greater operation and maintenance requirements, but without any commercial data on FBC it is difficult to assess any meaningful differences in employment levels.

New industries will probably not be created to produce the FBC technology; the boiler manufacturers appear quite interested and capable of capturing these markets. However, the phaseout of a boiler manufacturing plant and the introduction of a fluidized-bed component manufacturing facility may represent a catalyst that might stimulate and hasten industrial migration to a more economic site. Industrial migration of this type can be extremely socially disruptive, leaving many unemployed who are not capable of migrating with the industry.

4.4 RESOURCE USE

This section summarizes those aspects of the four system options relating to the use of resources, including energy, materials, water, land, and economic resources.

In general, the four systems do not differ greatly in resource use. Because heat rates fall within a close range, coal energy used and cooling water requirements are similar. The systems using high-sulfur coal differ in their consumption of sorbents and, consequently, in land required for solid waste disposal, although actual disposal techniques remain to be determined. Use of other material resources is comparable, with the possible exception of requirements for special materials from critical supplies, such as alloys for the PFBC turbines, although quantities of such materials are not likely to be significant.

4.4.1 Energy Resource Utilization

As the technology characterization indicates, heat rates for AFBC, PFBC, and LSC fall within five percent of that for FGD. Therefore, coal utilization by the systems is about the same on a Btu basis. However, the ability to burn high-sulfur coal in the FGD, AFBC, and PFBC options means that, in effect, more coal resource is available, and that eastern coals can be efficiently burned near demand centers. One possibility for improved coal utilization is that the clean coal obtained from a full beneficiation process can be burned more or less conventionally, with the remaining coal fractions used in plants which can handle the higher sulfur levels.

There is also little difference in terms of net energy output over the lifetime of the systems. Mining and hauling of sorbent material requires an additional ancillary energy input for the three systems utilizing a sulfur sorbent, in proportion to the amount consumed. Battelle data indicate that production of crushed limestone requires 0.12 million Btu/ton, including an average 200-mile haul.[1] Therefore, the sorbent accounts for less than 0.2 percent of the annual total energy input of the AFBC and PFBC and 0.1 percent of that of the FGD system. Disposal of spent sorbent also requires some energy, presumably a smaller amount. If the LSC were cleaned, additional energy would be required, but this ancillary energy is only on the order of 0.05 million Btu/ton.[2] Limited beneficiation may reduce the energy recovered from as-mined coal by five percent; more elaborate beneficiation may require ten percent or more.[3]

4.4.2 Materials Resource Utilization

Broadly speaking, there is little overall difference in the materials required to provide the capital equipment and facilities for the systems; the additional coal cleaning equipment for producing low-sulfur fuel from eastern coal, the equipment for FGD, and fluidized-bed equipment all representing perturbations on the basic coal fuel cycle. At a more detailed level, of course, differences among the systems occur due to variations in such factors as mining techniques and transportation, although these differences tend to be adjustments in quantity of materials, which do not raise significant concerns at the level of this report. A possible exception in the PFBC system is the gas turbine, which remains to be fully developed. Because of its severe operating environment, it may require special alloy metals, such as chromium or cobalt, which may be dependent on possibly insecure imports or otherwise not readily available materials. Although amounts required are not likely to be large, this and other possible critical materials requirements should be kept in mind.

In operation, the major differences involve sorbent use and disposal. In addition to its sulfur-removal properties, the sorbent must have appropriate particle size, impurity content, attrition resistance, and suitability for regeneration or disposal. Barring local or short-term supply problems, limestone and dolomite are generally abundant at low cost and are mined in regions where plants using sorbents would be located, such as Indiana, Ohio, and neighboring states. The Bureau of Mines reports a 1973 consumption of nearly 800 million short tons of limestone and dolomite, largely for aggregate and construction materials, cement manufacture, agriculture uses, and various chemical processes.[4] Therefore, the sorbent requirements of the system--135 to 350 thousand tons per year for one 500-MW plant--are relatively small. Sorbent regeneration is not considered economic at present. Speculation on uses for spent AFBC sorbent have been made; one possible use is in agriculture, as a soil amendment and nutrient.

4.4.3 Basic Natural Resources

Land requirements for all four systems are similar except for the disposal of spent sorbent, which largely remains to be determined. As discussed in the technology characterization, problems exist in dewatering the sludge from FGD plants, in forming stable materials for landfill, and in preventing leaching of wastes into water supplies. For the FBC systems, the disposal problems could be similar in amount of land required, although different in potential environmental effects.

Assuming that all systems use wet cooling towers, the water requirements will differ only according to the respective heat rates. The PFBC plant is more efficient, which reduces water requirements.

Considerations of the air resource are highly dependent on local conditions as well as details of plant design. The PFBC has lower NO_x emissions. It is assumed that all systems will meet SO_2 standards. These plant emissions affect air quality and may impact competing activities in the airshed.

4.4.4 Economic Resources

In terms of capital requirements for utilities, the LSC plant is some $100/kW cheaper (1975 dollars) than FGD, AFBC, and PFBC, although capital costs of the newer technologies are subject to more uncertainty. Of course, the more expensive options permit use of the more abundant high-sulfur coal. The LSC option requires more investment in fuel transportation facilities. Although FGD, AFBC, and PFBC increase the financing difficulties for utilities, there should be no significant differences in arrangements for utility financing among the systems. Additional investment is required in the equipment industries to produce new hardware, such as the PFBC turbine. Models such as the Bechtel Energy Supply Planning Model[5] and the INFORUM module of EPA's Strategic Environmental Assessment System[6] can be used to obtain estimates of direct and indirect materials and equipment.

All systems are assumed to have the same construction times and operating lifetimes. Manpower needs are about 500 persons per year over an average four years of construction for a 500-MW plant. The FGD system requires about 20 percent more persons for plant operation than the LSC system. The AFBC and PFBC concepts may require slightly more personnel for operation than an LSC plant. Data bases such as the Bechtel model give typical manpower job categories for construction and operation. There should be no major differences in categories of workers for the four systems.

Another class of impacts on economic resources results from the environmental effects of the systems. A sub-class of these impacts concerns the use and valuation of property, and includes the maintenance required to overcome soiling and deterioration of buildings, equipment, and clothing. These consequences are largely felt in an economic sense, affecting the allocation of money, manpower, and other resources. For example, if a technology option has greater particulate emissions, there may be increased soiling of buildings and clothing, requiring expenditures of funds which could have been used in other ways. Considering the energy-conversion facility, we find that these impacts should be much the same among all the options because the emissions will be about the same--except for the PFBC facility, which has lower particulate emissions. Emissions also occur due to surface mining and transportation of coal and of limestone or dolomite. These impacts, while undesirable to society, will not generally determine the choice of alternatives.

There are a number of other sub-classes of impacts. A severe aesthetic impact may reduce recreational uses of land and accompanying developments. In another case, the water quality problems caused by disposal of ash and sorbent might make certain agricultural activities impractical or mandate costly water treatment. Such impacts may then generate cycles of higher-order effects--for example, unemployment, if an economic activity ceases. We have not evaluated these impacts because they will be specific to geographical locations.

References for Section 4.4

1. Battelle Columbus Laboratories, "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 4--Energy Data and Flowsheets, High Priority Commodities)," pp. 16-22, prepared for U. S. Bureau of Mines, June 27, 1975.

2. University of Oklahoma, Science and Public Policy Program, Energy Alternatives: A Comparative Analysis, prepared for U. S. Council on Environmental Quality et al., May 1975.

3. P. J. Phillips and P. P. DeRiezo, "Steam Coal Preparation Economics." In: Second Symposium on Coal Preparation, NCA/BCR Coal Conference and Expo III, pp. 50-63, Louisville, KY, October 19-21, 1976.

4. U. S. Bureau of Mines, Minerals Yearbook, 1973, Vol. 1, pp. 164-165.

5. Bechtel Corporation, Energy Systems Group, The Energy Supply Planning Model, prepared for NSF, San Francisco, August 1975.

6. U. S. Environmental Protection Agency, Strategic Environmental Assessment System, Executive Summary (Draft), December 16, 1975; C. Almon et al., 1985: Interindustry Forecasts of the American Economy, Lexington Books, Lexington, MA, 1974.

4.5 SCENARIO AND COSTS

Section 4.5 discusses some non-technical factors that may influence the introduction of FBC technologies, namely, federal environmental standards, coal supply and demand on a regional basis, and bus-bar costs of electrical energy. Expected international developments of the FBC, industrial implementation of FBC technology, and variations in national energy use are not included in the discussion.

4.5.1 Potential Air Quality Regulation Revisions

Currently, emission standards for coal-fired power plants are controlled by the federal NSPS and by state regulations. If a state wishes to promulgate more stringent regulations than the NSPS it may do so, but it cannot set less stringent ones. The NSPS apply only to new and modified power sources; state regulations apply to both new and existing sources.

Potential revisions of the current NSPS for coal-fired plants (1.2 lb/million Btu for SO_2, 0.1 lb/million Btu for particulates, 0.7 lb/million Btu for NO_x) are being considered. EPA estimates that the time to review and possibly revise a regulation is five to seven years after it goes into effect. It is currently believed that EPA will suggest more stringent regulations for coal-fired power plants, especially for SO_2 and particulate emissions.

Revisions of state regulations do not appear to be a strong possibility at this time. Some revision is possible in air quality maintenance planning programs, but only in those areas of a state expected to experience significant growth and development. Recent EPA studies have focused on state regulations that could involve over-kill in their control of SO_2 emissions. Some changes were made, but these were not very extensive.

Some revisions to the control of air pollution using the National Ambient Air Quality Standards may have an impact on coal-fired power plants. Ambient air quality standards for lead are currently being developed. A short-term standard for NO_x, differentiated from the current annual average standard, is also being considered.

An EPA policy affecting the location of emission sources in areas that have not attained the National Ambient Air Quality Standards could have a significant impact. These areas, called non-attainment areas, may be limited in the amount of emission growth they can tolerate. The EPA policy states that sources wishing to locate in these areas or expand existing facilities there must first of all use the most reasonably available control technology; secondly, they must demonstrate that emissions will be reduced elsewhere at their facility to compensate for the increase in emissions from the new additions. This trade-off policy is still being circulated for public discussion; one possibility is that the emission reduction required may have to be better than one-to-one in order to allow the source to expand. Required use of control technology also indicates the possibility that standards more stringent than the NSPS may have to be met if a source is to locate in a non-attainment area.

A more significant area where regulation revisions are being contemplated is in "Prevention of Significant Deterioration" of air quality (PSD), being evaluated as part of the Clean Air Act amendments. This would limit the location of emission-producing facilities in areas now cleaner than National Ambient Air Quality standards require. One of the provisions of the PSD regulations is that sources locating in these clean-air areas may be required to use best available control technology. EPA has estimated that the best available control technology for coal-fired power plants would be the use of low-sulfur coal plus an 80 to 90 percent efficient scrubber. This could conceivably put regulations at an order of magnitude lower than the existing NSPS. These amendments to the Clean Air Act will be considered early in this session of Congress.

4.5.2 Coal Supply and Demand

To assess the potential level and geographic distribution of fluidized-bed market penetration, the following coal scenario has been developed. The coal utilization levels predicated are assumed to represent modest growth conditions for coal. Some key background conditions which characterize present energy trends are:

1. real annual price increases for oil of up to 5 percent per year;
2. continued decline in domestic oil and gas production;
3. no substantial changes in environmental restrictions on coal mining or combustion; and
4. a slowdown in the growth of electrical energy demand from the historical rate of about 7 percent per year to a more modest rate of about 5 percent per year.

Since the scenario describes the expected result of these trends in coal market conditions, it can be described as "surprise free." It projects the overall growth in domestic coal demand to be 4 percent per year to 1990 and 2.9 percent per year from then to the turn of the century. This compares with a demand growth of less than 1 percent per year during the period 1950 to 1970.

Coal demand data are presented on the basis of the U. S. Census Regions (Figure 4.1). Coal production required to meet these demands is presented on the basis of the five geophysical coal provinces shown in Figure 4.2.[1]

Electric utility demand (Table 4.5) and total coal production estimates (Table 4.6) are made for 1990 and 2000. These long-term projections were

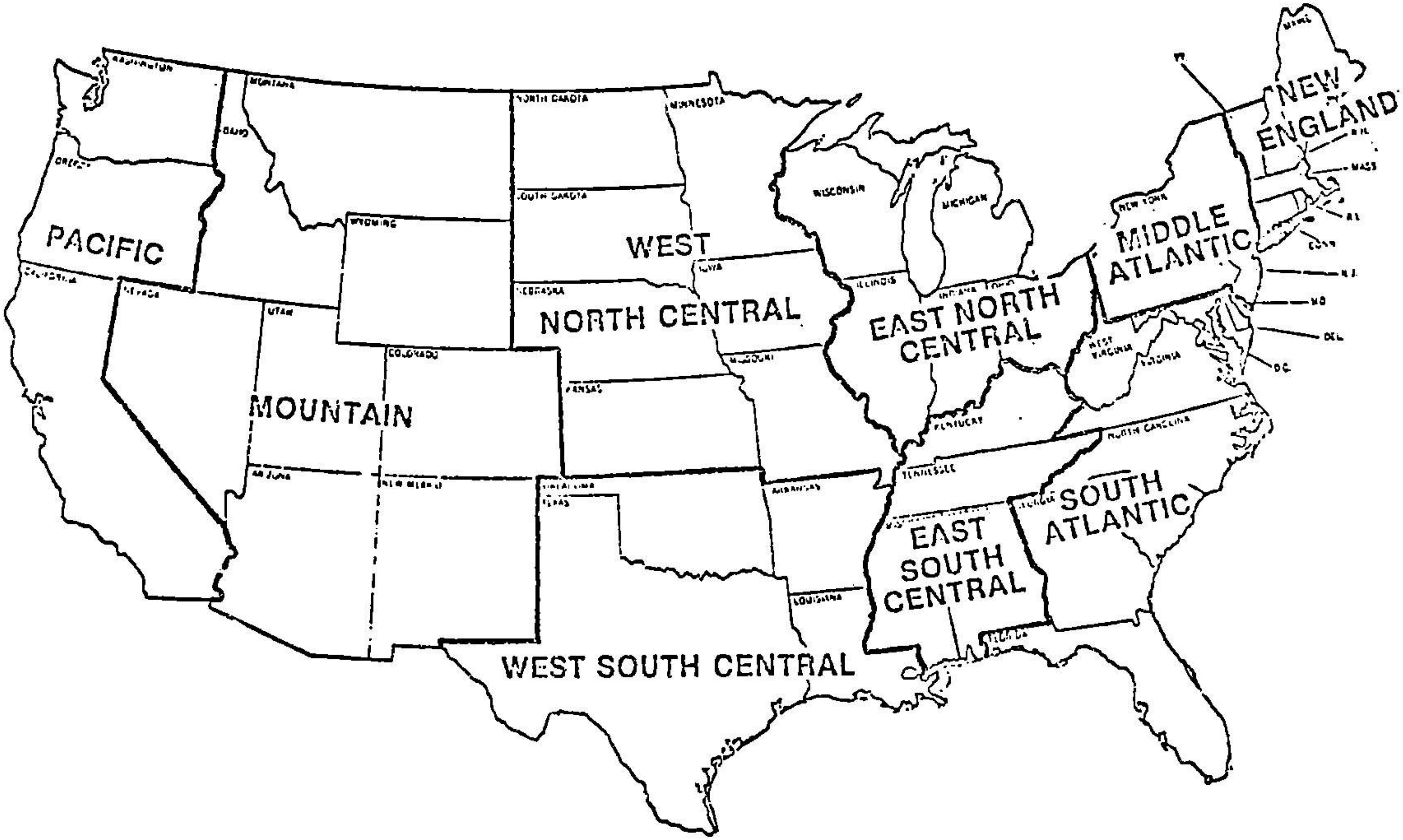

Fig. 4.1. Census Regions Used for Coal Demand Projections

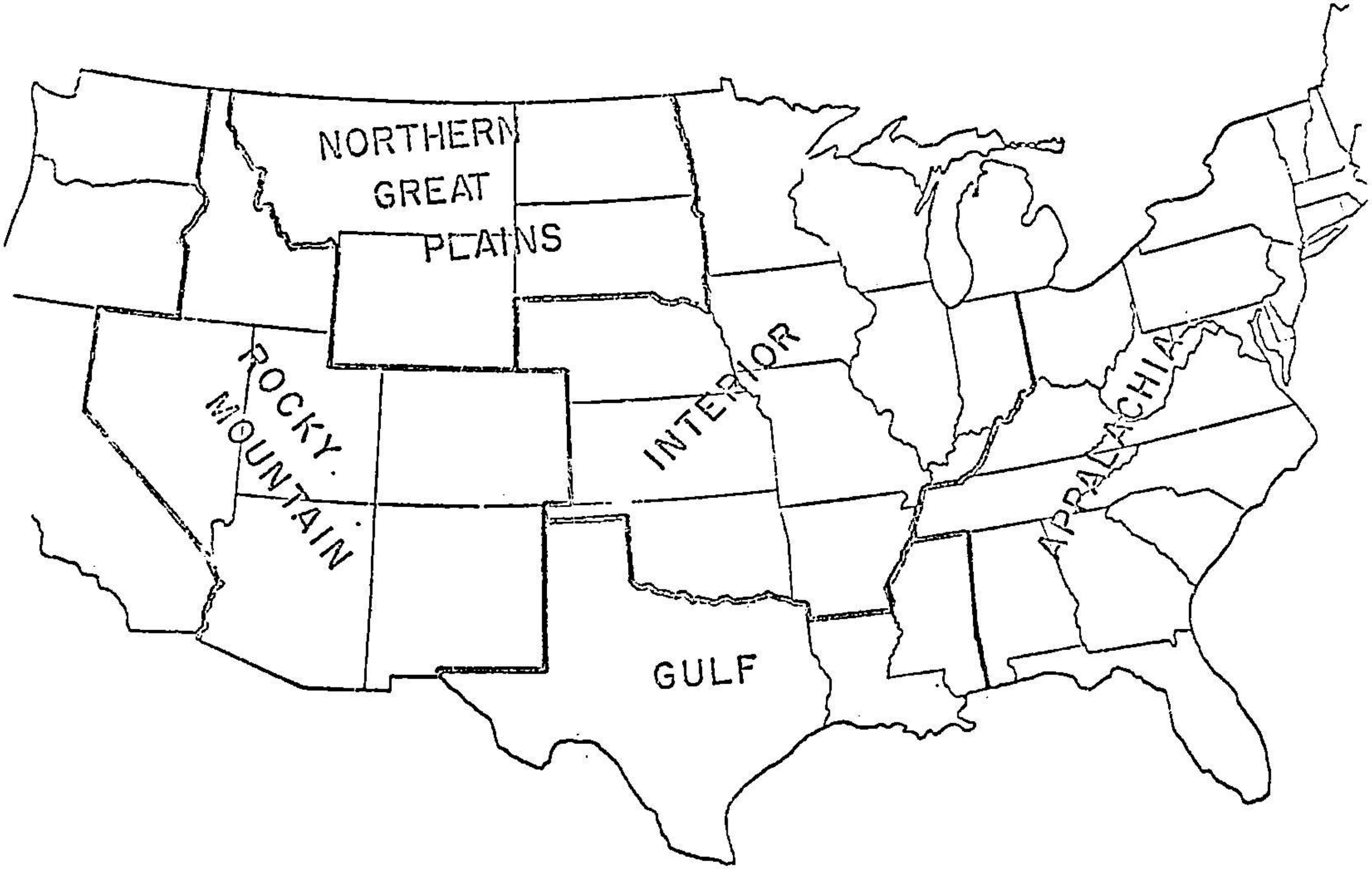

Fig. 4.2. Geophysical Coal Provinces

Table 4.5. Low-Sulfur[a] and High-Sulfur Coal Proportions of Utility Coal Demand, 10^6 tons/yr

Census Region	Low-Sulfur	High-Sulfur
	1990	
New England	neg[b]	6
Middle Atlantic	8	117
East North Central	97	114
West North Central	50	27
South Atlantic	26	124
East South Central	20	61
West South Central	15	35
Mountain	46	neg
Pacific	11	3
Total	273	487
	2000	
New England	neg	6
Middle Atlantic	10	150
East North Central	120	140
West North Central	68	36
South Atlantic	28	131
East South Central	21	63
West South Central	18	42
Mountain	52	neg
Pacific	13	4
Total	330	572

[a] Low-sulfur coal is defined as coal that can meet Federal NSPS without post-combustion controls.

[b] Negligible.

Table 4.6. Regional Coal Production by Sulfur Levels[a], 10^6 tons/yr

Region	Low Sulfur	High Sulfur	Total
	1990		
Appalachia	269	341	610
Interior	12	165	177
Gulf	neg	33	33
Northern Great Plains	218	40	258
Mountain	91	neg	91
Total	590	579	1169
	2000		
Appalachia	289	383	672
Interior	17	199	216
Gulf	neg	57	57
Northern Great Plains	401	70	471
Mountain	143	neg	143
Total	850	709	1559

[a] Includes foreign exports. Low-sulfur coal here includes metallurgical coal.

necessitated by the long lead times associated with the commercialization of FBC technology. The year 1988 is assumed to be the nominal date for commercialization of AFBC and 1995 the date for PFBC.

In this scenario, it is assumed that FBC becomes commercially available at the above times at an overall cost per kilowatt hour that is not materially different from FGD costs. This convention was adopted to maintain the relative economics of using low-sulfur coal and the overall demand for coal in any region. Without such an assumption, we could not perform this analysis on a short-term basis.

The principal purpose of including these demand and supply data is to create perspective on the regions potentially impacted by the FBC technologies. The data indicate that utility steam-coal demand is concentrated in a few regions: East North Central, South Atlantic, and Middle Atlantic. These three regions will account for over half of all steam coal used by electric utilities. The New England and Pacific regions, on the other hand, will account for less than three percent of utility coal demand.

Industrial steam coal demand is also relatively great in the East North Central region as well as in the Middle Atlantic states. The former alone will use almost half of all industrial steam coal by 1990, mainly for process heat. Overall, industrial demand for coal is expected to grow more rapidly than utility demand within the time frame considered here.

A critical factor affecting the market potential for sulfur-control technologies, such as scrubbers and FBC, is the price and availability of coal low enough in sulfur content to be burned without post-combustion controls. Within the category of low-sulfur coal, one should also include coal that can be cleaned, by present or advanced beneficiation technologies, to meet air emission standards.

To assess the potential long-term market penetration of low-sulfur coal, simulations were run with the Argonne Coal Market (ACM) model.[2] These simulations were done with a variety of assumptions regarding reserves, mining costs, and transportation charges. The results suggest that the long-term market penetration of western low-sulfur coal might extend as far east as Pennsylvania. Moreover, Northern Great Plains coal and some Rocky Mountain coals are expected to fill large boiler fuel markets in the Gulf states.

Fuel choice and supply patterns are relatively clear for the Far West. The Rocky Mountain and Great Plains states will generate virtually all of their additional power requirements from low-sulfur coal due to their ready access to it. The Pacific states will be barred from a great deal of coal use due to ambient air quality problems.

Along much of the eastern seaboard and in the South, coal-based electrical generation is relatively competitive and will be based on Appalachian production. Southern Appalachia has some extremely high-quality low-sulfur steam coal deposits, but they are expensive to mine. Production will probably be limited to 50 to 90 million tons per year, some of which will be exported to foreign nations.

The most volatile markets for coal occur in the Midcontinent, generally along the Mississippi River basin. On the eastern fringe of the basin, nuclear power competes heavily with coal, but in most of the area coal will be the predominant source of electrical power until the turn of the century. Competition between western low-sulfur coal and midwestern high-sulfur coal is very keen. It appears that, at present, western coal has a slight price advantage over scrubbers as far east as Ohio.* This cost advantage is reinforced by the uncertainty of sophisticated control options such as FGD. In the future, the Midwestern states may be a hotly contested market area for control technologies.

4.5.3 Costs

Comparative cost estimates for complex technologies, even those for which commercial operating experience exists, are at best only approximations based on a number of simplifying assumptions. The problems are even greater in comparing the costs of technologies for which little operating experience exists. This section attempts to characterize, in a general way, the relative economic costs of three major coal-conversion technologies: (1) conventional power plants using low-sulfur coal without stack cleanup, (2) conventional power plants using high-sulfur coal with flue-gas desulfurization, and (3) first-generation atmospheric fluidized-bed combustion with high-sulfur coal. In addition, PFBC technology costs are provided; however, because the date of commercialization is different, the costs are not strictly comparable.

**Western coal may even penetrate as far as Pennsylvania and New York, using inexpensive Great Lakes shipment.*

Table 4.7 compares the overall cost of generating electrical power from the three technologies in 1975 mills per kilowatt hour. Costs are broken down into a capital component, operation and maintenance, and a fuel component. The data indicate that, for Midwestern markets, low-sulfur western coal is a low-cost power option (25 to 28 mills/kWh). Moreover, the capital component for the use of low-sulfur coal appears to be substantially lower than that for other control options. The higher fuel costs associated with the use of low-sulfur coal are relatively acceptable to utilities, which can generally pass them on directly to customers.

The capital cost figures were taken from an EPRI study published in 1976 by Spencer,[3] and from the Energy Control Alternatives Study (ECAS),[4] which was also used by Spencer in making his estimates of relative capital requirements. A breakdown of capital costs taken from the ECAS study is given in Table 4.8; these costs are only slightly different from those used by Spencer and by us.

The range of capital cost estimates for AFBC and PFBC is derived from two independent assessments. In both studies, a new 800-MWe plant was assumed, operating at 65 percent of rated capacity.* Both studies also employed an 18 percent rate of return on capital. Finally, both studies are based on equipment required to meet Federal NSPS. Despite these important similarities, it is not clear whether provisions for contingency, cost escalation, and interest during construction were entirely equivalent.

The operating and maintenance costs contained in the ECAS study appeared to be unreasonably low. Alternative operating costs were therefore computed using a recent study by EPRI, current operating cost information from Commonwealth Edison, and information contained in the report, "Electric Utilities Study," by TRW, published in November, 1976.[5]

Fuel costs were recomputed from the ECAS study in order to make the three options comparable in terms of location and supply sources. The plants were

---

**Although our reference generating unit is 500-MWe, we do not believe that an 800-MWe size will change the relative economics.*

Table 4.7. Comparison of Electricity Costs from Alternative Generating Technologies that Comply with Federal New Source Performance Standards, 1975 mills/kWh

Cost Element	New Conventional Plant with Low-Sulfur Coal	New Conventional Plant with Scrubber	Fluidized-Bed Technologies	
			AFBC	PFBC
Capital Component[a]	14.5 - 11.9	19.8 - 15.3	21.0 - 14.2	22.1 - 14.5
Operation and Maintenance[b]	2.0	3.4	3.6	4.2
Fuel Component				
Transportation	7.6[c]	0.8[d]	0.8[d]	0.7[d]
Coal Price	3.6[c]	7.2[d]	7.2[d]	6.3[d]
Total	28.6 - 25.1	31.2 - 26.7	32.6 - 25.6	33.3 - 25.7

[a] Capital cost data are based on the EPRI study by D. Spencer for the LSC, FGD, and AFBC; the PFBC was estimated using the recent ECAS study.

[b] The ECAS operating costs were considered to be unrealistically low for all technologies considered, e.g., 2.2 to 1.0 mills/kWh for plants with scrubbers. Therefore, alternative estimates were computed using EPRI data and other sources.

[c] This represents the delivered cost of low-sulfur coal from the Powder River Basin to a representative Midwestern city, Springfield, Illinois.

[d] The delivered cost of high-sulfur Illinois coal to Springfield, Illinois.

Table 4.8. Comparison of Capital Costs Associated with Alternative Post-Combustion Sulfur-Control Technologies, $1974

	Conventional Plant[a] with Scrubber, $/kW	Fluidized-Bed[a] Technologies, $/kW	
		AFB	PFB
Furnace/Steamboiler	110 - 118	126 - 103	192 - 140
Stack-gas Cleanup	139 - 97	63 - 48	- -
Steam Turbogenerator	66 - 61	66 - 61	62 - 52
Gas Turbogenerator	- -	- -	58 - 36
Balance-of-plant	320 - 192	337 - 198	310 - 194
Total	635 - 468	592 - 410	622 - 422

[a] The left column is based on General Electric data; the right, from Westinghouse data. The cost analysis comes from Lewis Research Center, (Comparative Evaluation of Phase I Results from the Energy Conversion Alternatives Study (ECAS), February 1976, NTIS, Springfield, Va., p. 82.) Costs for each line item are all-inclusive, including applicable contingency, interest, and escalation. The cost basis is an enclosed-type construction with land cost excluded and without provision for on-site disposal of waste. Contingency applied to General Electric-based results is 15 percent. For interest and escalation we used the NASA factor of 1.49 for a five-year construction period. Costs assume an 800-MWe plant burning 3.9 percent sulfur coal.

all assumed to be sited in South Central Illinois (near Springfield). The low-sulfur coal is assumed to come from the Powder River field. High-sulfur coal for the two control technologies was calculated to come from Southern Illinois.

When the plants are operated as base-load units, the costs for all options fall into the same range. Regional differences will occur, of course. For mid-range operation the economic attractiveness of the low-sulfur alternative is noticeable because of its lower capital cost, which is a fixed cost. Annual capital charge rates lower than 18 percent would improve the economics of FGD, AFBC, and PFBC as compared with those of LSC.

References for Section 4.5

1. G. Krohm et al., "Candidate Scenarios for the Coal Utilization Assessment," Draft Report from Argonne, Lawrence Berkeley, Oak Ridge, Brookhaven, Los Alamos, and Pacific Northwest National Laboratories; published at Argonne, Illinois, September 1, 1976.

2. C. D. Dux, G. C. Krohm, and J. C. Van Kuiken, Modeling Long-Term Regional Coal Production, Draft Argonne National Laboratory Report, Argonne, Illinois, November 1976.

3. D. F. Spencer, "Clean Coal: What Does It Cost at the Busbar," EPRI Journal, November 1976.

4. Lewis Research Center, Comparative Evaluation of Phase I Results from the Energy Conversion Alternatives Study (ECAS), NTIS, Springfield, VA, February 1976.

5. TRW Corp., "Electric Utilities Study," Cleveland, OH, November 1976.

4.6 TECHNICAL DESCRIPTION AND CHARACTERIZATION OF THE TECHNOLOGIES

The technical characterization that follows describes the FBC and other technologies as they pertain to the assessment. For FGD and LSC technologies, the emphasis is on the emission controls. The FBC technologies are discussed in some detail, especially from the process viewpoint. That this information is more extensive than in some other environmentally oriented assessments, is due to our belief that the technical characterization is the basis for a meaningful assessment.

The main subdivisions in this section treat the fluidized-bed combustion of coal (4.6.1), control technologies for conventional combustion of coal (4.6.2), and a summary characterization of combustion options examined in this study (4.6.3).

4.6.1 Fluidized-Bed Combustion of Coal

A fluidized bed is a column of dense particles suspended in an upward-flowing air stream. Because the particles are moving so rapidly, as in a fluid, there is maximum heat transfer among the particles and to surfaces within the bed. Coal combustion in a fluidized bed containing added noncombustible solids is an efficient way to generate steam and electricity because it provides for efficient transfer of the heat of combustion to steam tubes immersed in the bed.

The development of FBC technology for coal, however, has been pursued less for its efficiency than for the opportunities it offers for control of SO_x emissions from utility and industrial boilers. If the solids fed to the combustor with the coal are calcium-containing sorbents such as limestone or dolomite, the SO_2 formed in the combustion process can be largely absorbed by the bed and removed with the spent solids. Development of the FBC technology both at atmospheric pressure (AFBC) and elevated pressures (PFBC) is under way, but commercialization is not likely before the late 1980s for AFBC and the mid-1990s for PFBC.

A number of important design and operating parameters affect the economics, efficiency, and environmental performance of fluidized-bed combustors. To a considerable extent the parameters are interrelated, and important trade-offs are involved in their optimization. Optimizations for commercial FBC boilers, when they become available, will depend not only on a set of environmental objectives but also on site-specific factors. Partly for this reason, and partly because experimental information is limited and subject to uncertainties in extrapolation from bench-scale investigations, it is difficult to make a definitive environmental assessment of FBC. Conclusions that are drawn must be accepted with some reservation and remain subject to confirmation as additional data accumulate and larger FBC units become operable.

4.6.1.1 Design and Operating Parameters

Pressure/Excess Air

Pressure has a major effect on system design for power generation and particulate removal. In AFBC, all electrical output is derived from steam generated by the transfer of heat to tubes immersed in the bed, and particulate removal from the combustor off-gas is the last operation before that gas is discharged to the stack. Excess air in the combustor is generally limited to about 20 percent to minimize thermal losses in the stack. In PFBC--usually carried out at pressures near 10 atm--energy in the hot (1650°F), pressurized gas leaving the combustor is recovered by expanding it through a gas turbine, and prior removal of particulates is required. When the level of excess air in PFBC is 20 percent, about 20 percent of the electricity is generated from the turbine. If the gas flow through the combustor is increased by increasing the amount of excess air, a point is reached--at about 300 percent excess air--when all of the heat is removed by the gas and the steam tubes in the bed can be eliminated. This type of operation is called adiabatic PFBC. Calculations indicate that combined-cycle PFBC will have a higher thermal efficiency than either AFBC or adiabatic PFBC.

The pressurized FBC options require highly efficient particulate removal (to about 0.01 $lb/10^6$ Btu), to prevent erosion of the turbine blades. Removal of 99.9 percent or more of the particulates is necessary to achieve this level. Cyclonic collectors are the only proven technology currently available for removal of particulates at high temperatures and pressures, but it is extremely doubtful that they can provide the required efficiency, especially for fine particulates. Improved types of high-temperature particulate removal devices, high-efficiency cyclones, granular bed filters, and porous metal and ceramic filters are under development, but the ultimate solution may also require improvements in turbine materials and design.

Pressurized operation also affects emissions of NO_x and CO, operating temperature/process economics, and sorbent selection. In experiments conducted under otherwise identical conditions, NO_x emissions of about 400 ppm at atmospheric pressure were reduced to 200 ppm at 8 atm; CO concentrations were reduced from 2000 ppm to 170 ppm. The reduction in emissions at elevated pressures has been attributed to the reaction between NO and CO to form N_2 and CO_2, as indicated in the equation below.

$$2NO + 2CO \rightarrow N_2 + 2CO_2 \qquad (1)$$

It is evident from this equation that increasing the pressure would promote the reaction and, for a given amount of excess air, would lead to lower emissions of NO_x. Emissions in combined-cycle PFBC would be expected, on this basis, to be lower than in AFBC. In adiabatic PFBC, however, the availability of CO is reduced by the large excess of oxygen and NO_x emissions would be expected to be higher than in the combined-cycle mode. The effects of pressure on sorbent selection and on operating temperature will be brought out in the discussion of these two topics which appears below.

Pressure may also have an effect on FBC economics. For a given lineal gas velocity and air/coal ratio, an increase in pressure in a fluidized-bed combustor permits passage of greater amounts of air and coal per unit time and a greater rate of heat removal. The capacity of a boiler with a given cross section can thus be increased by increasing the pressure; but as more heat-transfer surface must be submerged in the beds, deeper beds will be required. Since the size of boilers that can be shop-assembled and transported is determined largely by cross-sectional area, the capacity of boilers that can be pre-fabricated is higher for PFBC than for AFBC. This can be a substantial advantage considering the anticipated modular design of large power plants and the differences in cost between shop and site construction.

Sorbent Selection and Quantity

Limestone (a natural stone containing over 80% $CaCO_3$) and dolomite (a natural stone having approximately equimolar aggregates of calcium and magnesium carbonates, denoted by the formula $CaCO_3.MgCO_3$) are inexpensive sorbents that are widely abundant in eastern U. S. areas, where major deployment of FBC is anticipated.

It should be noted that the magnesium in dolomite does not absorb SO_2 under FBC conditions, and that to supply a given weight of calcium requires a dolomite input 1.8 times that of limestone and disposal of a correspondingly larger amount of solid waste. Differences in effectiveness of dolomite and limestone as sorbents, especially in PFBC, can compensate for the weight factor. Other criteria for selection of the sorbent include effectiveness of available stone, cost, attrition resistance, and suitability for regeneration/disposal.

The effectiveness of the FBC sorbents, aside from natural variations in specific samples, depends on the pressure and temperature used, and on the quantity added relative to SO_2 removed.

The activation of both limestone and dolomite for SO_2 absorption depends on the creation of a porous structure with a large internal surface area as a result of calcination reactions. Calcination of $CaCO_3$ occurs readily at bed temperatures in AFBC, but is inhibited at the higher pressures in PFBC. $CaCO_3$ is therefore relatively more effective as a sorbent in AFBC than in PFBC; for a given amount of calcium (Ca/S=2),* retention of sulfur in the bed has been found to decrease from 90 percent at atmospheric pressure to 70 percent at elevated pressure. The $MgCO_3$ component of dolomite is readily converted to the oxide at bed temperatures in both AFBC and PFBC, yielding MgO.CaO in the former case and "half-calcined" dolomite ($MgO.CaCO_3$) in the latter case. MgO itself does not absorb SO_2 under FBC conditions, but the porosity created by its formation facilitates the direct reaction of SO_2 with $CaCO_3$ in the half-calcined dolomite. The reactivity of dolomite may, in fact, be promoted by pressure; for Ca/S=1.5, retention of sulfur in the bed was observed to increase from 80 percent at atmospheric pressure to 90 percent at elevated pressures. Because of the inhibition of limestone calcination, dolomite is more effective than limestone at a given value of Ca/S in PFBC. After the stone becomes porous, absorption of SO_2 and oxidation to $CaSO_4$ occurs readily.

The quantity of sorbent required to remove a given fraction of SO_2 is a strong function of the superficial gas velocity and will be discussed further in that connection. It may be noted here, however, that 90 percent removal is generally achieved with quantities of sorbent in which Ca/S is 2 to 4 for $CaCO_3$ and 1.5 to 2 for dolomite.

The overall reactions of calcination and sulfation for limestone and for dolomite under AFBC and PFBC conditions are shown in the following equations.

Mole/mole ratio of calcium in the bed to sulfur in the coal; however, sometimes in the literature the ratio is based on sulfur absorbed.

Sorbent in Spent sorbent

$$\underline{r}CaCO_3 + SO_2 + \tfrac{1}{2}O_2 \xrightarrow[FBC]{\Delta} CaSO_4 + (\underline{r}-1)CaO + \underline{r}CO_2 \qquad (2)$$

$$\underline{r}MgCO_3.CaCO_3 + SO_2 + \tfrac{1}{2}O_2 \xrightarrow[AFBC]{\Delta} CaSO_4 + MgO + (\underline{r}-1)\ MgO.CaO_3 + 2\underline{r}CO_2 \qquad (3)$$

$$\underline{r}MgCO_3.CaCO_3 + SO_2 + \tfrac{1}{2}O_2 \xrightarrow[PFBC]{\Delta} CaSO_4 + MgO + (\underline{r}-1)\ MgO.CaCO_3 + (\underline{r}+1)\ CO_2 \qquad (4)$$

In these equations $\underline{r}$ represents the numerical value of Ca/S. The reactions have been included not only to illustrate the manner in which the composition of the spent sorbent depends upon $\underline{r}$, but also as basis for comment on factors affecting sorbent selection. It is evident from the first two equations that the use of dolomite rather than limestone at atmospheric pressure requires the input of additional heat (that required to produce $\underline{r}$MgO). For a given coal, the "energy penalty" obviously increases as $\underline{r}$ increases. What is not indicated in the equations is that the heat input from the combustion of coals decreases as the sulfur contents increase. A Pennsylvania coal with 3.1 percent sulfur and a heat content of 13,040 Btu/lb would supply 2.8 times as many Btu's per pound of sulfur retained as a Missouri coal with 5.39 percent sulfur and a heat content of 9421 Btu/lb. The heat absorbed for the reaction shown in Equation 3 is close to 5 percent of the heat input from the latter case, whereas it is less than 1.5 percent for the limestone reaction. If this were the sole consideration, use of limestone would be preferred to use of dolomite at atmospheric pressure, particularly for high-sulfur coals where higher values of $\underline{r}$ may be needed to meet standards. In practice, however, the choice of sorbent is based on additional considerations such as effectiveness per unit weight, cost, and, especially, resistance to decrepitation and attrition. The latter factor can be critical: For some stones the attrition rate is so high that a bed cannot be maintained; for others, the rate is sufficient to lead to unacceptable particulate levels. In one case a low-sulfur coal could not be started in a limestone bed, and when no other examples of the use of a low-sulfur coal with limestone addition were found, it was reported* that limestone may not be suitable for use with low-sulfur coals unless the starter

---

**J. E. Mesko, "Multicell Fluidized-Bed Boiler Design, Construction and Test Program," OCR 90 INTI (PB 236 254), August 1974.*

bed is heavily sulfated. Because emission restrictions in western states require desulfurization of low-sulfur coals, this point is an important one and merits further attention.

Superficial Gas Velocity

The superficial gas velocity is one of the most critical of all FBC parameters. As the flow rate is increased in a combustor of given cross-sectional area at constant excess air, coal throughput is increased, with potential increase in capacity or decrease in cost per unit capacity. (Correspondingly, use of a lower flow rate to increase sulfur retention and decrease particulate emissions, *vide infra*, will result in lower capacity or higher costs per unit capacity.) Because the potential for increased capacity can be realized only if the additional heat of combustion can be efficiently transferred to the steam tubes, and because the maximum expanded AFBC bed is only four feet, there are practical limits to the velocities that can be employed. Velocities used in AFBC have been in the range of 2 to 15 ft/sec; flow rates in PFBC have generally been less than 6 ft/sec.

A further limitation on the use of high flow rates is that combustion efficiency becomes unacceptably low due to carbon carryover, e.g.,

Velocity, ft/sec	Combustion Efficiency, %
12-14	85
8	85-91
3-4	89-97

One method of improving combustion efficiency is to use cyclones to capture the uncombusted carbon so that it can be recycled or fed to a carbon burnup cell (CBC). Recycling is likely to be less effective because elutriation will probably occur again, as it did in the first place. Use of a CBC with a fluidized bed operated at 2000°F with high (up to 50%) excess air will increase overall efficiency, but will also release sulfur carried by the carbon and produce some NO_x by thermal oxidation of N_2. Additional emissions of SO_x and NO_x will result from the necessary combustion of some coal in the CBC to maintain temperature. NO_x emissions from CBC tests have been shown to range from 350 to almost 800 ppm. The 30-MWe AFBC pilot plant at Rivesville, West Virginia, that is about to start operation, is designed for flow rates of 12 to 14 ft/sec and will use a CBC.

The superficial gas velocity also defines the size of particles which can be supported and maintained in the bed. At higher velocities the finer (more reactive) particles are rapidly elutriated from the bed. This results not only in increased particulate loadings in the combustor off-gas, but also in lower retention of sulfur in the bed. Sulfur retention at Ca/S=4 was observed to decrease from 85 percent at 3 ft/sec to 65 percent at 7 ft/sec; and even greater decreases were observed at lower Ca/S values. In another study (PFBC, dolomite), dust loadings at Ca/S=2 increased by 230 percent when the air velocity was increased from 2 ft/sec to 5 ft/sec; at a constant flow rate, dust loadings almost doubled as Ca/S was increased from 1 to 3. The dust loadings in the untreated gas ranged from 7 to 39 lb/10^6 Btu, compared to the 5 to 12 lb/10^6 Btu of fly ash typical of boilers fired with pulverized coal. Even higher levels have been observed (at higher gas velocities) in AFBC. Clearly, solids derived from the sorbent are present in the particulates from FBC combustors and can outweigh the fly ash.

Temperature

The highest thermal efficiency, subject of course to the allowable steam-cycle conditions, is obtained by designing the bed for operation at the highest practical temperature. The characteristics of the sorbents however, limit the operable range from 1400° to 1700°F for AFBC. Below 1400°F, the rate of reaction between the additive and SO_2 is too low, and at temperatures above 1700°F the reactivity (unaccountably) begins to decrease. In AFBC, with either limestone or dolomite, maximum sulfur retention has been found to occur at bed temperatures in the range of 1450° to 1550°F. The decrease in reactivity at higher temperatures is shown by the observation that sulfur retention by dolomite (Ca/S=2.2) fell from 90 percent at 1500°F to 15 percent at 1800°F. Similar effects have been observed with limestone; at Ca/S=4, retention fell from 96 percent at 1450°F to 60 percent at about 1670°F. It is evident from these results that, even though sorbent will be present in the CBC, sulfur retention (at 2000°F) will not be high.

In PFBC, sulfur retention has been observed to increase slightly as the bed temperature is raised from about 1450°F to 1700°F. The fact that operating temperatures can be higher in PFBC than in AFBC contributes to the higher efficiencies expected in PFBC.

Because of the low temperatures used in FBC and the uniformity of temperatures in fluidized beds, formation of thermal NO_x is small, and the NO_x that is observed must be derived largely from fuel NO_x. Bed characteristics and the availability of O_2 can therefore be important factors in NO_x emissions.

4.6.1.2 Characterization of FBC Emissions

From the foregoing discussion it is clear that an environmental assessment of FBC at a time when no integrated system has yet operated and most available data are from bench-scale studies, must be based on a series of assumptions regarding operation parameters and scale-up factors. There is no assurance that these assumptions will prove to be correct or even self-consistent.

To compare inputs, emissions, and residuals for FBC boilers with those of a conventional coal-fired power plant equipped with a limestone scrubber, a 500-MWe model plant was postulated, operating at a load factor of 0.75, and burning coal with 3 percent sulfur, 12 percent ash, and a heat content of 12,000 Btu/lb. For AFBC it was assumed that use of a limestone sorbent at Ca/S=3 will result in 90 percent removal of SO_2 and a plant heat rate of 9550 Btu/kWh. For combined-cycle PFBC it was assumed that use of a dolomite sorbent at Ca/S=1.5 would result in 90 percent removal of SO_2 and a plant heat rate of 8970 Btu/kWh. For the conventional plant, a heat rate of 9230 Btu/kWh with 90 percent removal of SO_2 using limestone at Ca/S=1.2 was assumed. This corresponds to use of state-of-the-art technology, as does the selection of NO_x emission levels of 300 to 400 ppm. In selecting NO_x emission levels of 350 to 450 ppm for AFBC and 150 to 300 ppm for PFBC, use of a CBC to maintain combustion efficiency was assumed. Particulate removal technology that would reduce levels to the 0.01 lb/10^6 Btu required for acceptable gas turbine operation is assumed to be incorporated in PFBC. NSPS for particulates are assumed to be met without incremental energy penalties by the use of conventional technology in the other cases. Inputs, effluents, and residuals associated with sulfur oxide control in the three options are shown in Table 4.9. The basis for the assumptions and additional aspects of pollutant emissions in FBC are discussed below.

Table 4.9. Effluents and Residuals in Sulfur Oxide Control[a]

	FGD	AFBC	PFBC
Heat rate, Btu/kWh	9230	9550	8970
Coal, ktons/yr	1280	1323	1245
Ca/S, mole/mole	1.2	3	1.5
Sorbent	$CaCO_3$	$CaCO_3$	$MgCO_3.CaCO_3$
Sorbent, k/tons	135	349	290
SO_2 emitted, ktons/yr	77	79	75
Spent sorbent (dry basis)	171[b]	291	315
Ash, dry ktons/yr	154	159	150
Total solids, ktons/yr	325	450	465
Wet, 50% solids	650	-	-
Fixed, 80% solids	405	-	-

[a] Basis: 500-MWe plant; 0.75 load factor; coal with 12,000 Btu/lb, 3% sulfur, and 12% ash; 90% sulfur removal. See text.

[b] Oxidation of $CaSO_3$ to $CaSO_4$ assumed to be 10%.

Thermal Efficiency

Only calculated values for the thermal efficiencies of AFBC and PFBC are available. One estimation, in which efficiencies are compared to that of conventional combustion with stack gas scrubbing for SO_2 removal, is:

	Conventional Plant with SO_2 Scrubbing	AFBC	PFBC
Plant Heat Rate, Btu/kWh	9230	9550	8970
Efficiency, %	37	36	38

Energy penalties in FBC depend to some extent on the Ca/S ratio and on the sulfur and heat contents of the coal; it is assumed that the tabulated values are appropriate for use of coal with 3 percent sulfur and a Ca/S ratio of 3 for AFBC using limestone and of 1.5 for PFBC using dolomite. Because the heat rates of AFBC and PFBC plants are within 5 percent of the conventional plants, the quantities of coal in the three cases are not greatly different, as is seen in Table 4.9.

Sulfur Dioxide

Sulfur-removal efficiencies depend to a large extent on the Ca/S ratio, the gas velocity and the temperature. A vast amount of data indicate that removal efficiencies of 90 percent can be obtained at moderate gas velocities with Ca/S values of 2 to 4 in AFBC and 1.5 to 2 in PFBC with dolomite sorbent. To calculate solids inputs and outputs, values for Ca/S that will result in 90 percent removal of SO_2 were assumed to be 3 for AFBC and 1.5 for PFBC. This assumption may or may not be compatible with gas velocities that might be selected for economic reasons in commercial FBC designs. It should also be noted that no information at all is available on incremental emissions of SO_x produced by the operation of CBCs. (It appears unlikely, however, that they could add more than 5 percent of fuel sulfur.)

Removal of 85 to 90 percent SO_2 is sufficient to meet NSPS except for a few coals with extremely high (>7%) sulfur content. In many western states, however, state/local regulations for SO_2 are more strict than NSPS and require desulfurization even when burning low-sulfur coals. Indeed, half of the planned 45,000-MWe stack-gas scrubber installations are for this purpose. Efforts in FBC have been concentrated on the use of high-sulfur coals and, as noted earlier (see Section 4.6.1.1, "Sorbent Selection and Quantity"), little information is available regarding applicability to low-sulfur coals.

Nitrogen Oxides

Measured values of NO_x emissions in AFBC range from 200 to 800 ppm; the average of 228 reported values is 350 ppm, and more than 90 percent of the values were below the 525-ppm level that corresponds to NSPS. Fewer results on NO_x emissions have been reported for PFBC, but available data suggest that emissions will be approximately half of those in AFBC.

Significant uncertainties are involved in assigning these values to commercial FBC installations. At FBC bed temperatures almost all of the NO_x formed is derived from fuel nitrogen, and emission levels depend heavily on specific reducing/oxidizing conditions in the bed. These conditions cannot readily be duplicated in scale-up. It is known that NO_x emissions in conventional pulverized-coal boilers, which are also formed predominantly from fuel nitrogen, increase with load.

The contribution of CBCs to the emissions must also be considered. NO_x emissions from these cells--which are expected to operate at 2000°F, with 50 percent excess air, and burn some coal to maintain temperature--can be 800 ppm. Since carbon carryover can be 15 percent, operation of the CBC can add as much as 50 to 100 ppm to emissions produced in the main bed.

Particulates

Particulate matter in the off-gas from FBC boilers can consist of fly ash, soot, unburned or partially burned coal, and calcined or sulfated SO_2 sorbents. Total amounts of particulates and relative amounts of the various components will be determined by the characteristics of the coal and sorbent and by the FBC conditions. The dust loadings, which increase with increasing gas velocity and Ca/S ratios, can be several times those in gases from a pulverized-coal boiler.

The particulates are not well characterized, and there are conflicting opinions regarding the mean size and size distribution of particles relative to those emitted from a pulverized-coal boiler. Although fly ash particles in

FBC have been reported to be significantly larger, other recent studies indicate a mass median diameter of 7 µm, with 10 to 15 percent of the mass less than 2 µm--not significantly different than in conventional combustion.

It seems unlikely that cyclones will provide adequate particulate removal, especially if there is a substantial fraction of fine material. In AFBC, where the primary and secondary cyclones can be followed by a conventional ESP or baghouse, attainment of NSPS is not anticipated to be a major problem. Low-temperature ESPs are not expected to be effective, as particulates in FBC have been found to have high resistivities (>10^{11} ohm-cm). The Rivesville plant will use a hot ESP, but information is not available on its performance for FBC particulates. Among the electric utilities, the use of baghouses for the collection of high-resistivity fly ash from low-sulfur coal is increasing.

In PFBC, where particulates must be removed at high temperature and pressure to levels an order of magnitude better than NSPS, the problem is a serious one. The inadequacy of cyclones for the 99.9+% efficiency required, and the efforts to develop new concepts have been noted earlier (Section 4.6.1.1). Until such technology becomes available, the array and magnitude of problems that may arise in integrated operation cannot be adequately addressed.

Trace Elements

Inventory studies on conventional coal-fired power plants have shown that some elements, such as Hg, F, Cl, Br, and to a lesser extent As and Se, are vaporized and leave with the flue gas. The latter two, as well as Cd, Cu, Ga, Sb, and Zn are partially vaporized and progressively become more concentrated in the fly ash than the bottom ash as the particle size decreases. Enrichments in the particles escaping collection can be more than an order of magnitude.

The limited data available indicate that trace-element emissions in FBC may be significantly different, in part because of the absence of high-temperature regions in the combustor and in part because of the presence of the sorbent. Most, if not all, of the Hg is lost, as in conventional combustion, but emissions of F, Br, and As are decreased. In the case of the halogens, absorption by the bed is responsible; it is probable that the As is also fixed, as calcium arsenate. The concentrations of several elements (Ba, Co, La, Sb, Sc, Ta) showed a slight tendency to increase with decreasing particle size of the ash, but no enrichments of the magnitude seen in conventional combustion were observed. (Note that Sb is one of the elements enriched in conventional combustion.)

Hydrocarbon Emissions

The so-called polynuclear aromatic hydrocarbons are of particular concern among hydrocarbon emissions inasmuch as some of these compounds, such as benz(a)pyrene, are known carcinogens. The relative rates of formation and decomposition of such compounds during the burning of coal are strongly dependent upon combustion conditions. Conditions leading to relatively low combustion temperatures, as is the case in fluidized-bed combustors, are especially suspect, since it is believed that compounds such as benz(a)pyrene may form more rapidly than they decompose at combustion temperatures of 1500° to 1700°F. It should be emphasized, however, that there is virtually no experimental information available at this time concerning the presence or concentration levels of such organic compounds in the emissions from fluidized-bed combustors. A preliminary result suggests that levels of POM, measured as the summation of ten polycyclic hydrocarbons, may be somewhat higher (2 to 3 mg/10^6 Btu) than in pulverized-coal boilers, which have emissions in the range of 200 to 1000 μg/10^6 Btu.

Other Forms and Sources of Pollutants

It is believed that effective control of pollutant emissions resulting from the transportation, handling, storage, and preparation of coal and stone; from cooling operations and waste-heat disposal; and from water treatment and usage at power plants equipped with fluidized-bed coal combustors, can be accomplished by standard industrial practices now in use at conventional coal-fired utility plants. The disposal of the spent stone will be discussed in the following section of this report.

Management of Solid Wastes

In addition to the not insignificant quantities of coal ash produced as a waste product by all coal-fired power plants, fluidized-bed facilities can be expected to produce even larger quantities of spent SO_2 sorbent. Typically, a 500-MWe fluidized-bed power plant without sorbent regeneration might be expected to produce about 1000 tons of partially sulfated limestone or dolomite each day, enough to cover a 40-acre field to a depth of about 5 feet in one year (cf. Table 4.9). Obviously, suitable provisions must be made for the disposal of this waste material in an environmentally acceptable manner.

In order to reduce the magnitude of this disposal problem and also to reduce the quantities of fresh limestone or dolomite that must be supplied, regeneration and reuse of spent sorbent would be highly desirable. An additional benefit would be that the sulfur captured by the sorbent might be recovered in marketable form. Such regeneration processes are under development and have been demonstrated on the bench-scale and sub-pilot-scale levels. However, there are significant technical problems still to be resolved, and the economic feasibility of providing regeneration facilities for commercial-scale fluidized-bed power plants is considered by many to be very questionable. It therefore seems reasonable to assume once-through sorbent operation.

The spent sorbent is a dry, particulate solid comprised mainly of coal ash, $CaSO_4$, CaO, $CaCO_3$, and (when dolomite is used) MgO. The relative amounts of these compounds depend upon the value of Ca/S used, as shown in Equations 2 to 4. Trace elements arising from impurities in the coal and the sorbent will also be present. Particle size may range from 1/4 inch down. It is reported that the material compacts well and that it has self-setting properties when exposed to the weather. Owing to the absence of $CaSO_3$, the spent sorbent is not expected to show the undesirable thixotropic properties associated with the sludge from wet scrubbers, even if exposed to water. Leaching tests have shown that leachates have a high pH and levels of calcium and sulfate that exceed water quality standards of 75 mg/l for calcium and 250 mg/l for sulfate.

Several possible uses for spent sorbent have been investigated (or at least proposed) as alternatives to disposal by landfill. Some of these offer the possibility that the utilities might actually be able to sell the waste product rather than have to pay someone to haul it away. Among the alternatives mentioned are:

1. use as an agricultural fertilizer and soil conditioner,
2. use as a gypsum substitute in the manufacture of wallboard and other products, and
3. use as filler material in the manufacture of cement and cinder blocks and for roadbed construction.

Of the alternatives cited, use for agricultural purposes would seem to be the most promising. For example, peanut growers customarily apply finely ground gypsum over the tops of the peanut plants at the early bloom stage to supply the calcium needs of peanut kernels and pods. Limited tests indicate that the spent sorbent from the fluidized-bed combustor is also a suitable material for this purpose. However, the abundance and low cost of natural gypsum reduce the chances for widespread acceptance of spent sorbent as a gypsum substitute in most areas of the nation. It is also reported that spent sorbent from fluidized-bed combustors is sufficiently high in calcium carbonate equivalence to suggest its use as a liming agent to correct excess soil acidity from high-nitrogen fertilizers. It has also been suggested that the sulfur content of spent sorbent may make it even more desirable as a soil conditioner.

4.6.1.3 Current Activity in FBC Development

The fluidized-bed combustor has been under development for many years, supported by several government agencies. Currently, ERDA is the lead agency in the national R&D program. The ERDA program on FBC is primarily process development oriented, whereas environmental studies are supported mainly by the EPA. One current EPA program is a comprehensive environmental characterization of FBC systems, the goal of which is to obtain all necessary environmental data over the full range of variables for the FBC process. The EPA program is divided into two areas: environmental assessment and control technology development. GCA Corporation/Technology Division has recently completed a preliminary environmental assessment which identified potential pollutants that have not received attention in past experimental work, but which may be emitted from fluidized-bed combustors. GCA also briefly assessed possible control technology for use on pollutants expected to be emitted in significant quantities.

Battelle has recently been awarded the contract for the primary environmental assessment of FBC. This effort comprises the following tasks: (1) to develop and compile background information on the current status of FBC process and environmentally related technology, (2) to perform a comprehensive analysis of emissions, (3) to develop the environmental objectives for the FBC process, (4) to assess the control technology potential of the process and any proposed supplemental control techniques, (5) to perform the environmental impact analysis of FBC, and (6) to develop the environmental R&D program.

As a part of Task 2 above, but under separate contract, Battelle is developing an approach for comprehensive analysis on FBC units and is to test the approach by conducting an analysis on the 6-inch I.D. unit at Battelle. Comprehensive analyses are also planned on the pressurized combustor at the British Coal Utilization Research Association; on a 7-foot I.D., pressurized, adiabatic, CPU-400 pilot plant at Combustion Power Company, with assistance by Aerotherm/Acurex Corporation and TRW, Inc.; on the 1-foot I.D., pressurized Miniplant facility at Exxon Research and Engineering Company; and on a variety of other planned FBC units, such as the pressurized Component Test and Integration Unit (CTIU) to be built at Argonne, as these units become available. The MITRE Corporation, as part of the comprehensive analysis effort, is preparing manuals for each of the FBC process variations, indicating alternative sampling and analytical procedures that can be employed for each variation.

Ralph Stone and Company has contracted with EPA to address specifically the question of solid and liquid waste disposal from FBC systems. In addition, the Tennessee Valley Authority, under an interagency agreement with EPA, is studying solid waste processing. In general, these studies involve: (1) characterization of solid and liquid waste materials from variations of the fluidized-bed combustion process; (2) laboratory and field studies to identify, e.g., solid leaching properties and the effect of long-term exposure of solid by-products to the environment; (3) laboratory studies of physical/chemical treatment of solid wastes to reduce the environmental impact upon disposal; and (4) laboratory and marketing studies of the potential for manufacturing marketable products from solid wastes.

ERDA and the USDA are cooperating in a $1.7 million, 5-year study of the use of FBC solid wastes for fertilizer and soil treatment. The project will include analyses of the wastes, followed by greenhouse and field studies. The material will also be tested for neutralizing acidity in strip-mined land.

EPA plans to build a small atmospheric-pressure sampling and analytical test rig at Research Triangle Park. Subjects to be studied on the rig include: (1) comprehensive analysis of emissions; (2) testing of alternative sampling and analytical techniques; and (3) investigation of alternative add-on control devices. An additional EPA effort by Dow Chemical Company will evaluate the effect of system size on emission from FBC systems of all known contaminants, including those for which experimental data may not be available. This information will provide an indication of the experimental scale on which environmental data may have to be obtained in order to enable reliable scale-up to commercial-size systems.

Exxon Research and Engineering Company, with EPA, ERDA, and FEA funding, is carrying out an energy, economic, and environmental assessment regarding application of coal-fired fluidized-bed boilers in the industrial sector. This study will result in projections of the applicability of coal-fired fluidized-bed combustion to industrial boilers; the technical requirements of envisioned industrial fluidized-bed boilers; the industrial demand for such boilers; the impact on the national energy situation of application of these boilers; the economic impact of the boilers on the industries employing them and on associated industries supplying the use industries; and the environmental impact of industrial coal-fired fluidized-bed boiler application. Although not specifically related to power generation, the results of this study should be applicable in that area.

The Tennessee Valley Authority is also conducting a project for EPA to develop conceptual designs and comparative capital and operating costs for an atmospheric-pressure fluidized-bed steam power plant, a pressurized fluidized-bed/combined-cycle power plant, and a conventional coal-fired steam power plant with flue-gas desulfurization. This effort is being carried out in coordination with the Energy Conversion Alternatives Study (ECAS) being undertaken by the National Aeronautics and Space Administration, the National Science Foundation, and ERDA.

In addition to funding FBC process development, ERDA is also funding the design and construction of pilot and demonstration plants. Pope, Evans, and Robbins have been responsible for the design, construction, and operation of a 30-MW AFBC unit at Rivesville, West Virginia. This unit will soon be in operation. In addition, ERDA is contributing to the design and construction of a 13-MW PFBC unit by Curtiss-Wright at Woodbridge, New Jersey. In support of these units, CTIUs are to be built for experimental evaluation of some of the operating parameters. The pilot-plant program will encompass the following tasks: (1) developing technology for stacking of the beds, (2) optimization of ash handling, (3) optimization of coal and sorbent feed systems, (4) optimization of boiler tube configurations, and (5) materials testing.

Additionally, ERDA is about to issue a request for proposals for the conceptual design of a 200-MW atmospheric fluidized-bed combustor. Another ERDA study will evaluate the applicability of using AFBC concepts in converting existing conventional power-generation systems, with emphasis on 10- to 20-year-old plants with the greatest environmental impact. ERDA Fossil Energy is participating in a study with HUD, NASA, DOC (NBS), EPA, HEW, and DOD in the use of AFBC in Modular Integrated Utility Systems (MIUS) for the decentralization of power-generation plants. Pope, Evans, and Robbins have contracted with ERDA to develop a 0.5-MW AFBC unit applicable to this project. The Tennessee Valley Authority has announced that it will spend $4 million on the preliminary design and support studies for a 200-MW demonstration plant using AFBC.

The Electric Power Research Institute has expressed interest in FBC. Projects under way include studies on heat transfer and solids distribution, optimizing the heat-transfer advantages of tubes submerged in a fluidized bed, corrosion and erosion characteristics of the tube materials, and an engineering assessment of available data from a boiler manufacturer's point of view.

Based on quantitative results from this work, design and construction of a 6 x 6-foot AFBC are being undertaken by Babcock and Wilcox. The combustor, scheduled for operation in September 1977, will be used to develop the large-scale mechanics of solids distribution and heat transfer.

Comprehensive reviews and assessments of the situation regarding the emission and control of pollutants from the fluidized-bed combustion of coal have appeared in recent reports prepared for the EPA by Westinghouse Research Laboratories and by GCA Corporation, and for the Electric Power Research Institute by Babcock and Wilcox. Studies of a similar nature are currently being conducted for the EPA by Battelle-Columbus Laboratories and by Dow Chemical Company.

FBC units put into operation have varied in size from three inches in diameter up to the 30-MW Rivesville plant about to start operation. Conceptual designs have been prepared for even larger installations. A PFBC plant of about 300 MW is expected to consist of four parallel modules, each consisting of four 5 x 7-foot fluidized-beds positioned vertically. An AFBC plant of this capacity is expected to have the same number and configuration of beds, but of much larger (ca. 100 ft^2) area. The gas velocity in the AFBC unit is expected to be higher.

Most of the operating experience in FBC has been with the smaller laboratory and development units. Reactors with long operating experience are in most cases less than 2 feet in diameter, but a few larger units are in operation. The Combustion Power Company's unit is 6 feet in diameter, and the British are now testing a steam-generating unit in Scotland that has a bed area of 100 ft^2.

These units have been constructed and operated for a variety of purposes. Some were intended for use in studying the combustion process, and others for studying heat transfer or air pollution. The Rivesville plant is the first to be designed to operate as an integrated unit and generate electricity. Only as data on its operation become available will some of the many uncertainties that prevail today become clarified.

4.6.2 Control Technology for Conventional Combustion of Coal

The current electric utility practices and state-of-the-art developments for pollution control in conventional combustion form a baseline case against which the emerging technologies must be evaluated and be able to compete. More than 400 million tons of coal per year, two-thirds of total U. S. consumption, are burned by utilities for electricity generation. Roughly 90 percent of this coal is burned in pulverized-coal furnaces equipped, for the most part, with electrostatic precipitators (ESP) for particulate control. At present, only about 3 percent of the 200,000-MWe coal-fired generating capacity is equipped with FGD systems, but plans for the installation of more than 45,000 MWe of "scrubbers" have been reported. The use of low excess air in combustion is commonly employed to reduce NO_x formation; more effective combustion modification technology has already been developed and field-tested, but is not yet in common use. The characterization and quantification of other atmospheric emissions--such as trace metals and carcinogenic compounds--is under way, but much additional information is needed. Ash disposal practices are being improved to control water pollution, and chemical fixation of FGD sludges to make them suitable for landfill is being developed.

In the sections that follow, this overview will be expanded to characterize the baseline case in greater detail.

4.6.2.1 Thermal Efficiency

Almost all utility furnaces now being manufactured are dry-bottom pulverized coal-fired units (pc-fired furnaces). Almost all coals, including low-sulfur western coals and lignites, can be burned in such furnaces without technical problems if the units have been designed for that purpose. The best new plants have heat rates of about 8800 Btu/kWh at 100 percent load and without added controls. The heat rate of units using low-sulfur western coals may be four to five percent higher because of their higher moisture content and the need for additional pulverizer capacity. The energy penalties associated with control of other pollutants will be noted in the appropriate discussions.

4.6.2.2 Emission Controls

NO_x Control

The nitrogen oxides emitted by combustion sources are predominantly in the form of NO, with the balance (usually less than 5%) in the form of NO_2. In the atmosphere, NO enters into complex chemical and photochemical cycles and is rapidly converted to the more hazardous NO_2. NSPS for coal-fired boilers limit NO_x emissions to the equivalent of 0.7 lb of $NO_2/10^6$ Btu (2 hours average), which corresponds to an NO_x concentration of $\sim$525 ppm (dry, 3% excess O_2) in the stack gas.

The formation of NO_x during combustion occurs in two distinct ways: by the fixation of molecular nitrogen in combustion air at high temperature (thermal NO_x) and by the oxidation of chemically bound nitrogen in the fuel (fuel NO_x). Both reactions are kinetically controlled, and their rates increase with increasing oxygen concentrations, but they have a markedly different temperature dependence. Fuel NO_x is relatively insensitive to temperature; formation of thermal NO_x, on the other hand, does not become significant until about 3300°F, but doubles thereafter for every increase of 70°F. The relative contributions of thermal and fuel NO_x therefore depend upon the combustor design and operating conditions as well as on the nitrogen content of the fuel. Tests in laboratory burners simulating the operation of modern pc-fired furnaces have shown (1) that fuel NO_x can account for more than 75 percent of total NO_x, and (2) that typically only a small fraction of the fuel nitrogen (15-40%, depending largely on the amount of excess air) is converted to NO_x. These results clearly indicate that combustion modifications designed to limit the availability of oxygen, such as use of low excess air (LEA) and staged combustion (SC), will be considerably more effective than those designed to reduce peak flame temperature. Furnaces now being built are designed for LEA operation and meet NSPS for NO_x when operated under design conditions. Some units are being built with dual registers or overfire air ports to facilitate SC operation. In recent tests a 400-MWe tangentially fired boiler achieved a NO_x emissions level of 300 ppm at full load. Other tests have shown that, with proper system design and operation, modified combustion does not lead to increased emissions of CO or hydrocarbons. No energy penalties are associated with the combustion-modification approach to NO_x control, and incremental capital costs are significant. Concern has been expressed, however, regarding the possibility of corrosion in staged combustion as a result of localized reducing conditions. Long-term corrosion tests are now under way to establish whether this will be a serious problem.

Another approach to NO_x control is burner design. A small-scale pc-fired single burner has already achieved NO_x levels of 150 ppm. The goal of this development is to achieve 200 ppm NO_x on a full-scale optimum single burner by 1977, with application by 1980.

It is possible that the recent increase in emphasis on stationary-source NO_x control will lead to significant reduction in permissible levels. Such an action could require removal of NO_x after formation by flue-gas treatment. Methods involving reduction with NH_3 in the stack, or simultaneous SO_2/NO_x removal in wet scrubbers (after oxidation to NO_2 with ozone) are under development in Japan, but thus far have not been applied to coal-fired boilers. These methods will be costly, as the reagents alone are quite expensive.

Particulate Control

In dry-bottom pc-fired furnaces about 80 percent of the coal ash is entrained in the flue gas as fly ash, giving dust loadings in the range of 5 to 12 lb/10^6 Btu. Collection efficiencies of 99.0 to 99.5 percent are thus required to achieve the NSPS of 0.1 lb/10^6 Btu. ESPs are routinely used and, where the resistivity of the fly ash is low ($<10^9$ ohm-cm), as with coals of moderate sulfur content, can achieve the required efficiencies with specific collecting areas of 200 ft^2/1000 acfm, corresponding to a cost of \$15 to

\$20/kW. Where required, collection efficiencies of 99.8 percent can be achieved without an unreasonable increase in size and cost. Low-sulfur coals, however, yield fly ash of high resistivity ($>10^{11}$ ohm-cm). For a collection efficiency of 99.5 percent, an ESP for the low-sulfur coal might be 2 to 2.5 times as big and costly as one for coal of a moderate sulfur content. The effects of high resistivity can be ameliorated to some extent by the deliberate injection of SO_3, or of other substances that can promote electrical charging into the flue gas. They can also be reduced by injection of substances that promote the agglomeration of fly-ash particles. The use of such conditioning agents is increasing markedly; whether or not these practices result in adverse secondary emissions has not been determined. Alternatively, a hot side ESP could be used. No energy penalties are associated with ESP usage.

A further problem with ESP is that collection efficiencies are markedly lower for particles in the 0.2 to 1.0 μm size range that are not readily charged by either diffusion or field charging. An ESP with an overall mass efficiency of 99.5 percent or higher might have an efficiency of only 90 percent for 0.5-μm particles. By weight, about 10 to 15 percent of fly ash will be ≤1 μm in size. These respirable particles are a source of much concern because they become lodged in the lower respiratory area and subject surrounding tissue to adsorbed trace metals and carcinogens for extended periods. For this reason, there is a distinct possibility that restrictions will be placed on the emission of fine (<2 μm) particulates. It should be noted in this context that incremental increases in the efficiency of an ESP become progressively more difficult and costly to obtain because an ever increasing fraction of residual particles is in the size range most difficult to collect.

In view of the problems with low-sulfur coals, utilities in recent years have investigated two other options for particulate collection: wet scrubbers and fabric filters. A limited number (about 20) of scrubbers have been installed either for particulate collection alone or in conjunction with SO_2 removal. These scrubbers normally operate with a high pressure drop, ranging from four inches of water for a high-pressure spray to 20 inches or more for a high-energy venturi. Overall collection efficiencies of 99 percent or more can be obtained, but energy penalties of three to four percent are incurred.

Problems with scaling, corrosion, and erosion have limited the availability of units and increased plant maintenance costs. Control of water pollution in disposal of the wastes has also added to costs. There is also some suggestion in recent work that the particles escaping collection in a wet scrubber may be more highly enriched in some trace elements than those escaping from an ESP with the same overall efficiency. For these reasons the use of scrubbers for particulate removal is not expected to become widespread.

A few other utilities have installed or are planning to install bag houses to overcome problems with high-resistivity ash. Initial results on collection efficiencies have been encouraging (>99 percent on a mass basis for particles down to 1 μm and >99 percent on a number basis for particles between 0.0023 and 0.5 μm). The longer-than-expected bag life (up to three years) suggests that fabric filtration may be economically competitive, and additional larger installations are planned.

Trace Elements

It has been known for some time that almost all of the mercury and a large fraction of fluoride and chloride present in coal are vaporized during combustion and emitted to the atmosphere. Several recent studies have shown that other trace elements regarded as toxic are partially volatilized during combustion and then condense on fly ash, preferentially on the smaller particles. Elements showing pronounced enrichment factors on fly ash include As, Cd, Cu, Ga, Pb, Sb, Se, and Zn. In some cases, concentrations on particles of 1 μm size was an order of magnitude greater than on larger particles, but it should be pointed out that the enrichment factors will vary with the combustion conditions and that results obtained from a cyclone furnace (as in some of the reports) may not apply to a pc-fired furnace.

Hydrocarbons

Total hydrocarbon emissions in pc-fired furnaces are low (ca. 0.02 lb/ton coal) even when low NO_x combustion modifications are used. Emissions of polycyclic organic matter, which are largely due to incomplete combustion, are also low from utility boilers. These emissions vary somewhat with the type of firing, but generally fall in the range of 200 to 1000 $\mu g/10^6$ Btu for pc-fired furnaces.

4.6.2.3 Flue Gas Desulfurization (FGD)

FGD is the generic name used to denote processes for the chemical and physical removal of SO_2 from flue gas, usually by means of a gas-scrubbing operation. The feasibility of achieving SO_2 removal at 85 to 95 percent efficiency from both high- and low-sulfur coals by FGD has been demonstrated unequivocally at commercial (>100 MWe) scale, but appreciable controversy still exists concerning the reliability, the costs, and the waste disposal problems associated with FGD systems. Nonetheless FGD is the only available option that will allow a utility to burn high-sulfur coal and still meet NSPS for SO_2 emissions (1.2 $lb/10^6$ Btu). It is also the only option available for compliance with more strict state/local regulations that require reduction of SO_2 emissions even when burning low-sulfur coal. It is noteworthy that FGD systems planned by the utilities are divided about equally between the two types of applications.

FGD systems can be of various types. They are termed <u>wet</u> processes if the SO_2 is absorbed in a scrubbing operation and dry if the SO_2 is absorbed on or reacts with a solid. They are termed <u>throw away</u> if the sulfur product is worthless, and <u>regenerable</u> if the product is marketable (e.g., sulfur or sulfur acid). Efforts in the U. S. have concentrated on wet, throw-away processes, especially those involving use of lime or limestone (L/LS) slurries, either (1) as the direct SO_2 absorbent or (2) indirectly, as in the double alkali process where L/LS slurries are used to regenerate the primary sodium base absorbent. In both cases a sludge is produced that is difficult to dewater and cannot be used for landfill without chemical processing. No regenerable process has been satisfactorily demonstrated at commercial scale in the U. S. thus far, but a demonstration of the Wellman-Lord process will begin early in 1977 and demonstrations of the Citrate process, the aqueous carbonate process, and possibly of magnesium oxide scrubbing are planned.

These appear to be the only processes that could become commercially competitive by 1985. Brief descriptions of these processes will be presented, with emphasis on L/LS processes, before considering present and planned deployment of FGD.

Process Description

In wet FGD processes in general, cooled and particulate-free flue gas enters the scrubber (a spray tower, venturi, or mobile bed absorber) where the SO_2 is absorbed by intimate contact with a circulating solution or slurry. The flue gas then passes through a mist eliminator to remove aerosols and through a reheater to restore its buoyancy. The energy expended in overcoming the pressure drop in the gas train, in the gas reheat, and in liquid and solid handling generally amounts to about four percent of plant output. An additional three to five percent is required in the case of regenerable processes for the restoration of sorbent activity and, in some cases, for the reduction of SO_2 to sulfur. (In the case of lime scrubbing, the equivalent of 1.6 percent of plant output is expended offsite for calcination of limestone.)

Use of lime and limestone are similar in many respects. In both cases the SO_2-rich slurries leaving the scrubber are sent to a hold tank (sized to allow an appropriate reaction time) where fresh slurry (ca. 10% solids) is added and a slip stream is withdrawn to a solids-handling stage (a pond, thickener, centrifuge, or filter) where spent solids are separated and the clarified liquor is returned to the scrubber system. In both cases, 85 to 90 percent removal of SO_2 is readily attainable. There are important differences in the two processes, however. In the case of lime FGD, a stoichiometric ratio of sorbent is used (Ca/S = 1) and the only calcium salts in the slurry liquor are $CaSO_3 \cdot 1/2\ H_2O$ and some $CaSO_4 \cdot 2H_2O$ formed by oxidation.

In the case of limestone FGD, Ca/S = 1.2 typically and the slurry contains unreacted $CaCO_3$ in addition to the sulfite and sulfate. The degree of oxidation of sulfite to sulfate, which is of importance with respect both to scrubber operation and sludge disposal, varies with the process and the sulfur content of the coal. It is generally higher for limestone (10 to 20%) than for lime

(5 to 10%), and much higher (ca. 80%) for low-sulfur coals. The sulfate content of the liquor is important to scrubber operation because $CaSO_4$ has a strong tendency to become supersaturated and, unless conditions are properly controlled, this leads to scaling and plugging of the scrubber and the mist eliminator. The sulfate content of the discard streams affects waste disposal because $CaSO_4 \cdot 2\ H_2O$ forms big blocky crystals, whereas $CaSO_3 \cdot 1/2\ H_2O$ forms fine platelets that tend to retain water; sludges containing higher fractions of sulfate can therefore be dewatered more easily and effectively. A sludge high in sulfate might dewater to 65 percent solids by vacuum filtration, whereas one high in sulfite might be limited to 40 percent solids; a solids content of about 80 percent is needed to support machinery and construction.

In the double alkali process, the circulating absorbent is a solution of sodium bases (derived from initial addition to sodium carbonate). The spent liquor leaving the scrubber, containing $NaHSO_3$ and Na_2SO_4, is sent to a regenerator where limestone and lime are added, the latter being required to regenerate the Na_2SO_4. The calcium solids are separated by filtration, washed with make-up water to remove sodium salts, and the filtrate returned to the scrubber system. The double alkali process is relatively new, but it appears to be rapidly gaining favor. Although there is little improvement in the quality of the waste sludges, scaling problems in the scrubber are minimized, and higher efficiences for removal of SO_2 (up to 95%) are possible. Two commercial-scale systems are under construction at the present time. Extensive commercialization could occur by 1985.

Among the regenerable processes the Wellman-Lord is the most highly developed. Like the double alkali process, it utilizes a sodium-base absorbent, but the sorbent is regenerated and the SO_2 is recovered (in concentrated form) by thermal stripping in an evaporative crystallizer. The Na_2SO_4 formed (ca. 6%) is, of course, not regenerable and is withdrawn in a bleed stream. The SO_2 stream can be condensed, oxidized to H_2SO_4, or reduced to sulfur. In the demonstration expected to start up in 1977, at the 115-MWe Mitchell Station of Northern Indiana Public Service Company, the SO_2 will be reduced to sulfur with natural gas. Construction of two commercial installations is under way at a western site. If the economics of the process are not unattractive, it too could see extensive commercialization by 1985.

The Citrate process developed by the Bureau of Mines uses a buffered solution of sodium citrate, citric acid, and sodium thiosulfate as the absorbent. Absorbed SO_2 is reacted with H_2S to precipitate elemental sulfur and regenerate the solution for recycle. The H_2S for the reduction is made by reacting two-thirds of the recovered sulfur with natural gas and steam. The bleed stream of Na_2SO_4 is small since the thiosulfate ion depresses oxidation of bisulfite. A full-scale demonstration of the process, supported by the Bureau, has been announced.

In the rather novel aqueous carbonate process, the SO_2 is absorbed by exposure to the solution in a spray dryer. The dry solids are mixed with carbon (char or coal) and are blown by air into molten sodium carbonate (1000°C) where reduction to sodium sulfide occurs. The reduction mixture is quenched, filtered, and carbonated (with off-gas from the reducer) to evolve hydrogen sulfide. The sodium carbonate solution is recycled and H_2S is converted to sulfur in a Claus reactor. The various steps of the process have been tested only separately. Eight New York state utilities and the EPA have initiated a four-year ($22 million) test of the process at the 100-MWe, coal-fired Huntley station of Niagara Mohawk.

In magnesium oxide scrubbing the solids formed by absorption of SO_2 ($MgSO_3 \cdot 3\ H_2O$, $MgSO_3 \cdot 7\ H_2O$, and $MgSO_4 \cdot 7\ H_2O$) are removed by centrifugation and dried. They are then heated at 1900°F in the presence of carbon (char) to regenerate MgO and evolve a stream of SO_2 sufficiently concentrated for use in the manufacture of sulfuric acid. Economic considerations dictate that the FGD solids generated at the utility be shipped to a sulfuric acid plant for regeneration.

The process was earlier demonstrated on an oil-fired boiler at the Mystic Station of Boston Edison (with support by the EPA) and on a coal-fired boiler at the Dickerson Station of Potomac Electric Power. Regeneration of the product in both cases was carried out at a chemical company in Rhode Island. Moderately satisfactory operation was eventually achieved at the Mystic Station, but losses of magnesium oxide were high (ca. 10%) and the number of regeneration cycles never exceeded five. Substantial improvement in both areas is required for acceptable commercial operation. Operation of the coal-fired Dickerson Station was never very satisfactory and is best described as a learning experience. The FGD units at both of these sites are now inactive. A magnesium oxide scrubbing unit installed at the Eddystone Station of Philadelphia Electric Co. is currently being used only for particulate collection.

FGD Deployment

In July 1976 it was reported (by PEDCo, under EPA sponsorship) that 27 FGD systems were operating on 5573 MWe. In 20 of these systems L/LS slurries were used directly; in two they were used in conjunction with the double alkali process. Of the three regenerable processes included, only one was actually operating (the Japanese Chiyoda 101 process for gypsum production).

It was further reported that a total of 113 FGD systems, controlling 42,735 MWe, were operating under construction or planned. An analysis of this report revealed that systems planned for operation by 1980 totaled only 32,210 MWe, with one-half being installed on plants in the east, burning coal with a sulfur content greater than one percent, and one-half installed on plants in the west, burning coal with less than one percent sulfur. (Use of L/LS slurries was selected in more than 90 percent of the cases where a process was already specified.) Only one-fifth of the 80,000-MWe of coal-fired capacity east of the Mississippi that burned non-complying coal in 1975 will have FGD by 1980. Installation of more than 30,000 MWe of coal-fired plants east of theMississippi in the period 1980-85 is planned. Unless the rate of FGD deployment accelerates, a large number of these plants will be burning either non-complying or low-sulfur coal in 1985. The expansion plans of the coal mining industry indeed call for addition of 278 million tons per year to steam-coal production in the west and a net addition of only 25 million tons in the east.

The sheer number of FGD systems planned suggests acceptance by the utilities, but the poor performance of systems currently operating is difficult to reconcile with such a conclusion. Of the 27 "operating" systems, only two of those installed on plants larger than 100 MWe have demonstrated the ability to operate with a reliability of 80 percent for a year or more. Among the plants recently installed, however, several are reported to be operating reliably, and their continued success could have an accelerating effect on FGD deployment in the 1980s (lead times for FGD installations can be four years or more). If, on the other hand, the optimistic reports prove to be premature, an increase in demand for low-sulfur coal could be anticipated.

An economic analysis of the two options does little to clarify the situation. Incremental capital costs of FGD, compared to low-sulfur coal, are estimated at $60 to $70/kW; operating costs, including waste disposal, may be 2 to 3 mills/kWh more. On the basis of these estimates, use of low-sulfur coal becomes attractive if the premium is less than 40¢/10^6 Btu (ca. $8/ton). The calculation does suggest that use of low-sulfur coal is competitive, at least in states adjacent to the Mississippi River. If the newer FGD installations continue to perform successfully, however, it would not be unreasonable to expect deployment of about 70,000 MWe of FGD by 1985.

4.6.2.4 Waste Disposal

In the combustion of low-sulfur coal, the only solid waste will be fly ash. In the past, ash was commonly sluiced to an on-site pond. It can be anticipated, however, that it will become increasingly common to pneumatically transport the ash to the disposal or export site. At present, about 10 million tons/yr of ash, one-sixth of the total amount of fly ash and bottom ash produced, is utilized, chiefly as a component in portland cement compositions, in pavements, for blast grit and roof granules, and for soil stabilization. The National Ash Association is attempting to promote the use of coal ash, and has succeeded in increasing the annual tonnage, but not the percentage, of ash utilized.

A 1000-MWe base-load power plant burning coal with the average amount (12%) of ash will produce about 300,000 tons of ash per year. Compacted ash occupies about one cubic yard per ton, and disposal of the ash over the (30 year) lifetime of the plant will require about 120 acres, covered to a depth of 30 feet.

The disposal of the unused ash involves potential problems of pollution of surface and subsurface water. The ash consists chiefly of the oxides of silicon, aluminum, and iron, but most of the trace elements present in the coal are also present in the ash. In a recent investigation of leachates from a number of ash ponds, it was found that concentrations of As, Ba, B, Cr, Hg, Mo, and Se exceeded one or more of the water quality criteria at one or more of the power plants, sometimes by an order of magnitude. The leachability of various species in the ash will be determined largely by solubility; generally about two to five percent of the fly ash is soluble in water. The resulting solution is usually alkaline due to the presence of free lime, but some ashes from eastern coals produce acid leachates. In these acidic liquors, concentrations of sulfate, iron, zinc, lead, cadmium, and manganese often exceed criteria for discharge into streams. Attenuation of the leachate contents by percolation through soil is expected in many cases to provide substantial protection against trace elements reaching an aquifer, but disposal sites will need to be monitored and controlled.

Potential contamination of groundwater by leachates can be reduced by preventing or diverting flows of surface and subsurface waters, e.g., by maintaining a suitable system of subsurface and trench drains. Protection against erosion and liquefaction can be achieved by good compaction, proper drainage, and development of a suitable vegetative cover.

Ash does not readily support plant growth, due partly to its lack of the necessary nutrients and partly to the presence of toxins. Some elements present in the ash, such as B, Mn, Cu, Zn, and Mo, are essential to plant growth, but are toxic in higher concentrations. Boron, in particular, may be 20 times as available in fresh ash as in normal soil. Other elements, such as Se, As, Cd, Be, Pb, and Cr are not essential and can be toxic. Accumulation of Se in plants grown in ash has been noted.

It seems reasonable to conclude at this time that, while ash disposal continues to pose an environmental problem, the problem is not much worse than other waste disposal situations and is one that can be managed by careful monitoring and by optimum employment of currently available technology.

The problems involved in the disposal of wastes from lime or limestone scrubbing (or the double alkali process) are much greater because the crystalline nature of the calcium sulfite hemihydrate makes it impossible to physically dewater the sludges to the extent required to support weight. As noted earlier, the sludges can contain varying amounts of $CaSO_4$ and of unreacted $CaCO_3$, but the major component in sludges from high-sulfur coals is the troublesome sulfite. The sludges can also contain varying amounts of fly ash--from a few percent when particulates are collected dry prior to scrubbing, up to the total weight of the ash when collection is incorporated with the FGD process. The behavior of representative sludges in ponding and in vacuum filtration is shown in Table 4.10. It may be noted that the solids content of high-sulfite sludges increases with ash content (but not enough to permit compaction). For this reason, separately collected fly ash has usually been combined with scrubber slurries before ponding or dewatering by centrifugation or vacuum filtration.

The ponding of such mixtures presents many problems. The permeability of the mixtures is low (10^{-4} cm/sec, 100 ft/yr), and problems arising from the leaching of trace elements will be similar to those encountered in the disposal of fly ash alone. Leachates from such wastes have been found to contain various trace metals (As, Cd, Cr, Pb, Hg, and Se) in amounts exceeding EPA Proposed Public Water Supply Intake Criteria. Hg and Se exceeded the criteria by more

Table 4.10. Comparison of Typical Sludge Dewatering Properties

	Approximate Degree of Dewatering, % solids		
Sludge Type	Settling	Filtration	Approximate Percent Solids for Optimum Compaction
High $CaSO_3 \cdot 1/2\ H_2O$ (low fly ash)	30-35	50	80
High $CaSO_3 \cdot 1/2\ H_2O$ (high fly ash)	35-40	55-60	80
High $CaSO_4 \cdot 2\ H_2O$ (low fly ash)	60-65	80	90

than an order of magnitude in every case. Leaching of the calcium solids can give rise to excessive oxygen demand and total dissolved solids. An impervious liner of clay, cement, or synthetics will therefore be required for the pond. An overriding objection to simple ponding of the sludges, however, is the fact that reclamation of the land is not possible and large areas of land are permanently withdrawn from use. The weight of dry calcium solids from L/LS FGD of a coal containing three percent sulfur and 12 percent ash is approximately equal to that of the ash. Since the ponded sludge/ash mixtures contain only about 50 percent solids, whereas ash ponded alone contains 80 percent solids, the area required for disposal of the sludge/ash mixture is more than three times that for the ash alone. About 400 acres ponded to a depth of 30 feet would be required to dispose of the sludge from a 1000-MWe plant burning coal with three percent sulfur and 12 percent ash over its lifetime. Expressed somewhat differently, the sludge produced in the first ten years of operation of such a plant would cover one square mile to a depth of ten feet. It can be anticipated that as more FGD systems come on line, simple ponding will not be permitted, particularly because other options are available or being developed.

Chemical fixation of L/LS sludges is already being carried out at a number of FGD installations. Several proprietary additives are available that can be used to increase the compressive strength and decrease the permeability of the sludge/ash mixture. Quantities of additives corresponding to five to ten percent of the weight of the dry calcium solids are sufficient to lead to formation of a low-grade concrete from sludges that have been adequately dewatered. In the most ambitious fixation project, thickened slurry will be mixed with additive and pumped seven miles to the disposal area: a large ravine in which a 450-foot-high dam has been constructed. The life of the disposal area, for two 880-MWe plants, is estimated at 30 years.

Other utilities have concocted their own fixation recipes, adding a few percent of lime or portland cement and sometimes additional fly ash. In at least one case, the fixed sludge has been certified by EPA for and actually used in a landfill operation. Unconfined compressive strengths of 2 tons/ft^2 on 1:1 sludge/fly ash mixtures fixed by addition of three to five percent lime have been obtained after a 30-day cure. Leaching tests of sludges fixed with proprietary additives and cured have shown permeabilities in the range of 10^{-6} to 10^{-7} cm/sec, within the limits of acceptability for landfill. One of the more uncertain aspects of FGD economics, however, is the projected costs of fixing, transporting, and disposing of the wastes. Better definition of these costs, as well as realistic information on the capital and operating costs of regenerable FGD processes, is needed to determine the proper direction for further developmental efforts on FGD.

4.6.3 Summary Characterization of Options

4.6.3.1 General Similarities

1. Heat rates of FBC processes are within five percent of those of FGD (AFBC and LSC are 5% greater, PFBC is 5% less). Consequently, coal use (on a Btu basis) and cooling requirements do not differ significantly.

2. Physical conditions at stack exit are comparable. Because air/coal ratios are similar (15 to 20% excess air in all cases) and exit temperatures are similar (250° to 300°F), flue gas exit velocity and dispersion can be considered to be the same.

4.6.3.2 SO_2 Emissions (NSPS = 1.2 lb $SO_2/10^6$Btu)

1. FGD - 90 percent removal of sulfur oxides is achievable, regardless of the sulfur content of coal, with a Ca/S ratio of 1.2 in limestone scrubbing and 1.0 in lime scrubbing.

2. AFBC - 90 percent removal is achievable with Ca/S ratios of 2 to 4 (depending on reactivity of the sorbent limestone). If a CBC is used, removal efficiency may be limited to 85 percent. Excessive elutriation of limestone has been encountered with low-sulfur coals in some cases.

3. PFBC - 90 percent removal is achievable with Ca/S ratios of 1.5 to 2, depending on the reactivity of the sorbent dolomite (1.84 times as much dolomite as limestone is required to provide a given weight of calcium).

4. LSC - Restricted to coals with sulfur contents less than 0.6 lb/10^6 Btu.

4.6.3.3 NO_x Emissions (NSPS ca. 525 ppm)

1. FGD - Modern pulverized coal furnaces operating with low excess air and staged combustion emit 300 to 400 ppm NO_x; less than 10 percent of this is absorbed in the scrubber.

2. AFBC - Average of 231 data points is 350 ppm; 90 percent of the values fall below 525 ppm. If a CBC is required, emissions might be higher by 50 to 70 ppm.

3. PFBC - Expected to fall in the range 150 to 300 ppm.

4. LSC - Expected, as in FGD, to be 300 to 400 ppm.

4.6.3.4 Particulate Emissions (NSPS = 0.1 lb/10^6 Btu)

1. FGD - In modern pulverized coal furnaces, 70 to 80 percent of the coal ash is entrained, producing particulate levels in the range of 5 to 12 lbs/10^6 Btu; the required removal efficiency of 99.0 to 99.5 percent is achievable with conventional electrostatic precipitators. About 10 to 15 percent of the particulates (mass basis) are less than 2 μm in diameter. Some elements (As, Cd, Cu, Ga, Pb, Sb, Se, and Zn) are more concentrated in the fly ash than in the bottom ash and even more concentrated in the finer fly ash escaping collection.

2. AFBC - The particulate matter in AFBC will differ from that in FGD and will consist of CaO, $CaSO_4$, fly ash, and some soot. Dust loadings in untreated gas increase with increasing sorbent/coal ratios and fluidizing gas velocity, and can be from 2 to 5 times those in conventional combustion. There are conflicting opinions on the size of the particles relative to those in conventional combustion; some recent studies indicate that the fraction below 2 to 3 μm may not be significantly different. If this is the case, it may not be possible to meet NSPS using only cyclones. The particles have high electrical resistivity ($>10^{10}$ ohm-cm), making the use of a conventional cold ESP impractical. A hot ESP is to be used in the 30-MW Rivesville, West Virginia, FBC plant, but no data are available to permit prediction of its performance. Some data suggest there will be less enrichment of trace elements on the finer fly ash particles. Because of the carbon content there may be some problems with respect to opacity.

3. PFBC - Dust loadings before treatment are expected to be lower than for AFBC but still above those in conventional combustion. Particulate removal to levels below NSPS may be required to minimize erosion of the gas turbine blades; such technology is not currently available but is under development. Particulate matter in PFBC will include $CaCO_3$, $CaSO_4$, MgO, and a small amount of CaO in addition to the fly ash. The trace element content will resemble that in AFBC.

4. LSC - As for FGD, 70 to 80 percent of the ash will be entrained. The resistivity of the fly ash is higher in the LSC case, but NSPS are still achievable with conventional electrostatic precipitators or baghouses, although at increased cost.

4.6.3.5 Hydrocarbon Emissions

1. FGD and LSC - Total hydrocarbon emissions in pulverized coal furnaces are low (ca. 0.02 lb/ton coal) even when low NO_x combustion modifications are used. The utility boilers are also only minor

sources of POM. POM emissions vary somewhat with the type of firing, but generally fall in the range of 0.2 to 1 mg/10^6 Btu.

2. AFBC and PFBC - No data on emissions of hydrocarbons and POM have appeared in the literature, but preliminary data suggest that POM emissions, as vapors and particulates, may be somewhat higher than in conventional combustion, in the range of 2 to 3 mg/10^6 Btu.

4.6.3.6 Other Hazardous Atmospheric Emissions

1. Metals - As in conventional combustion, almost all Hg is emitted in FBC; some Pb is also emitted.

2. Halogens - Significant retention of F, Cl, and Br occurs on the limestone additives in FBC. Retention of As and Se may also occur. Atmospheric emissions are lower for these elements.

4.6.3.7 Solid Wastes

1. FGD - In lime/limestone scrubbing the calcium salts are rejected in the form of a slurry that is difficult to dewater beyond 40 percent solids. Even if the sludge is mixed with fly ash it can only be dewatered to the extent of 50 to 60 percent solids, insufficient for landfill suitability. Leachates from such wastes have been found to contain various trace metals (As, Cd, Cr, Pb, Hg, and Se) in amounts exceeding EPA Proposed Public Water Supply Intake Criteria. Hg and Se exceeded the criteria by more than an order of magnitude in every case. Disposal by ponding would therefore require an impervious lining. Possibilities for utilization of the sludge are remote. Alternatively, the sludge-fly ash mixtures can be chemically fixed by addition of five to ten percent of CaO or one of several proprietary additives. Fixed sludges have sufficiently low permeability ($<10^{-6}$ cm/sec) and high compressibility to be used for landfill. At an eventual solids content of 80 percent, the volume of fixed sludge

from a coal with three percent sulfur and 12 percent ash is roughly twice that of the fly ash alone.

2. AFBC - The spent sorbent removed from the bed is largely a mixture of CaO and $CaSO_4$; their proportions depend on the Ca/S ratio used. A recent demonstration program has shown that regeneration of limestone sorbent is not economic if the stone costs less than \$16/ton, and once-through use is likely. Some of the spent sorbent may find use as a soil amendment and nutrient, but large-scale utilization is not likely. Since leachates have a high pH and show considerable extraction of calcium and sulfate, disposal presents problems. Techniques for acceptable disposal have not yet been worked out.

3. PFBC - The spent sorbent in this case is a mixture of $CaSO_4$, $CaCO_3$, MgO, and a small amount of CaO, again in proportions that depend on the Ca/S ratio. Disposal problems are similar to those in AFBC, but somewhat less severe because of the lower solubility of magnesium salts.

4. LSC - The only solid wastes are fly ash and bottom ash. Ponding of the ash from a 500-MWe plant to a 30-foot depth over a 30-year period requires about 5 acres for each percent of ash in the coal burned.

4.6.3.8 Effluents and Residuals in Sulfur Oxide Control

(See Table 4.9, section 4.6.1.2.)

4.6.3.9 Water Pollutant Emissions from FBC and Alternatives

Table 4.11 lists emissions of waterborne effluents from fluidized-bed and conventional power plants. Due to the lack of information on FBC emissions, estimates were obtained on a comparative basis drawn from actual operating data of conventional power plants.

Table 4.11. Waterborne Effluents, FBC and FGD

Element	Discharges, lb/day 500-MW FBC, 75% Load Factor	 500-MW Conventional, 75% Load Factor
TSS	93 max 28 avg	189 max 57 avg
Oil and grease	19 max 14 avg	38 max 28 avg
Ammonia nitrogen	0.92	1.4
Nitrate nitrogen	0.17	1.2
Chloride	91	127
f.a. Chlorine	9.2 max 3.5 avg	9.2 max 3.5 avg
Sulfate	133	270
Fe	20	21
Cu	4.8	4.8
Zn	0.44	0.47
Cr	0.60	0.62
P	4.8	4.8
Na	67	143
Ni	4.8	4.8
Mg	106	116.0

The numbers here are based on unit 500-MW plants operating at 75 percent load factor. The differences in thermal efficiencies between the technologies were insufficient to warrant distinction between cooling-system size, i.e., evaporative water use. Mechanical-draft wet cooling towers with a circulating flow of 500 gpm/MW and a blowdown of 0.8 percent were assumed throughout.

Emission rates are based on ash handling water (conventional only), boiler blowdowns, boiler cleaning, and low-volume wastes such as floor drains, with a maximum total discharge volume of 2 x 10^6 gal/day. NSPS were met wherever applicable. Fly ash was considered to be handled pneumatically in all cases. It was assumed that the bottom ash and spent sorbent were handled dry from the FBCs, while the bottom ash was handled and ponded wet in the conventional systems. This amounts to the only distinguishable difference between FBC and conventional boilers that can be ascertained at this time. It is possible to handle the bottom ash from the pulverized cool furnaces pneumatically also, so that this difference could be eliminated.

There is no evidence to indicate that FBCs will require unusual means of feedwater treatment or will have significantly different emissions from boiler cleaning. The quality of the input makeup water and the preferences of the individual utilities are much greater influences on the characteristics of these emissions.

Note that there is no distinction made between the low-sulfur coal and the high-sulfur coal with FGD alternatives. This was made possible by assuming a state-of-the-art SO_2 scrubber operating in the closed-loop mode for disposable sorbents.

Small amounts of trace metals were discharged in addition. Data are available only for ash handling wastewater in conventional plants. These are shown in Table 4.12. Additional loadings from other sources may well occur.

Table 4.12. Trace Metal Discharges, FBC and FGD

	Discharges, lb/day	
Pollutant	FBC	Conventional
Al	U	1.2
Mn	U	0.05
Cd	U	0.01
Se	U	0.05
As	U	0.01
B	U	0.05
Pb	U	0.01
Ba	U	0.07

U = Unknown

4.7 RESEARCH AND DEVELOPMENT

Throughout the study, primary assessment activities were not directed toward developing a description of environmental and health R&D needs for the FBC technology. Rather, as a by-product of the assessment, the assessors were directed to state the areas where they thought R&D was needed. There was no effort to structure R&D by reviewing activities presently occurring or planned and then identifying the niche for some uncovered need. Indeed, the use of information presented here by the ERDA analyzer required his identification of needs related to his programs.

In general, the research and development mentioned here show research needs caused by the transition of a technology from the bench and experimental scale to a demonstration and prototype scale. Our findings regarding R&D needs in the areas of engineering, human health, and environmental protection will be briefly described.

4.7.1 Engineering

In order to make health and environmental assessments of the FBC technology, work in three engineering areas is required: collection of emissions data under various large-scale operating conditions, examination of designs and operating conditions for a unit burning low-sulfur fuel, and development of engineering specifications for spent sorbent waste disposal.

The first area requires collection of source information from large FBC facilities. The emissions from the operation of large-scale prototypic FBC installations could change in quantity and character from those calculated theoretically or estimated on the basis of bench-scale experiments. It is urged that assessments be planned and coordinated with the operation of such facilities so that the emission information is indeed obtained and the analyses conducted on a timely basis. A systems approach to link the measurements, changes in design parameters, and estimated impacts should be used.

The second area where engineering definition is required relates to the ability of the AFBC to use various bituminous coals and lignite. From some experiments, it appears that the AFBC cannot use some low-sulfur (<2%) fuel: i.e., the bed combustion cannot be started and maintained because the mechanical characteristics of the sorbent material are degraded. It has been indicated that changes in materials could overcome this problem. These changes in materials could change predicted plant emissions and waste disposal. Although the health and safety impacts might not be noticeably altered, knowledge about the technology's applicability to a range of fuels seems fundamental in an assessment, especially in a comparative assessment where the combustor for the competing technology can be designed to handle these fuels.

The last area relates to engineering specifications for the disposal of spent sorbent or spent sorbent and ash. The possibility of using the dry form of the waste for beneficial uses such as soil amendment has been suggested. Considering the history of fly-ash use and disposal, we believe that in a large number of cases the spent sorbent must be conditioned and used as landfill. The engineering details of this treatment and disposal are necessary to quantify cost, health, and environmental impacts.

4.7.2 Human Health

4.7.2.1 Source Information

At this point, we can make only educated guesses as to what the large-scale emission sources will be, and we can project their effects only by using crude dose-response models based on index pollutants, which may or may not correlate well with the biologically active components of FBC effluents. We need to determine what will be inhaled by persons who breathe an atmosphere into which FBC effluent has been introduced. This will include not only the effluents emitted from the stack, but also secondary reaction products formed in the effluent plume as it disperses. Hence, there is a need for:

1. detailed information on the composition and chemistry of the effluent stream as it leaves the stack, and

2. information on the atmospheric chemistry of these components and their interactions, and their interactions with other pollutants from other sources.

4.7.2.2 Studies of Synergisms Between Pollutants

The available toxicological studies indicate that, for exposure to multicomponent mixtures of atmospheric pollutants, the total health effect will not be equal to the sum of the individual effects of the components inhaled individually, but rather that both synergistic and antagonistic effects must be considered. We can only guess these effects in the case of some of the heavy metals and trace elements. It is not known how hydrocarbons, $CaSO_4$ particles, soot particles, nitrogen oxides, and other components will interact with the trace elements and with each other.

We therefore need toxicological studies, not only of many of the individual components, but also carefully considered combinations of these components. We would recommend the following sequence of studies:

1. Inhalation experiments of FBC-generated smoke, both fresh and following processing, to simulate some of the atmospheric reactions leading to secondary products;

2. Reduction of the effluents studied in (1) to increasingly smaller subgroups of components in order to isolate the synergistic relationships of interest;

3. Simultaneous development of inexpensive Ames-style tests which can be used for monitoring total air quality as affected by FBC effluent streams. This will facilitate the early detection of potentially harmful situations without the necessity of relying on potentially misleading index pollutants.

4.7.2.3 Epidemiological Studies

Because FBC is a completely new technology, no existing human population has ever been exposed to its effluent streams. Hence, no direct observation of human health impacts is possible at this time. However, once the source terms have been adequately characterized, it may be possible to locate populations which have been exposed to roughly similar effluent combinations for statistically significant periods of time. For example, a population living downwind of both an oil refinery and a gypsum plant might fit in this category. Properly conducted field studies could then be used in conjunction with the laboratory results recommended above for projecting future health effects.

Careful studies should be made of some of the populations exposed to the first few FBC plants to go into operation. Baseline and operational studies would be made. Such studies would:

1. identify and quantify the health effects which occur in a real population prior to exposure to FBC-generated effluents;

2. identify subgroups within the exposed populations showing higher-than-normal risk of suffering ill effects. This higher-risk group can be more or less defined in advance--the aged, chronically ill, smokers, and very young children. However, it is not known how each of these groups will respond to the effluent stream here considered; and

3. analyze the health effects of the impacted region a few years after FBC plant startup.

4.7.3 Environment

The following information has been taken directly from the section containing the backup information for the environmental assessment. For the context in which these needs were stated, the reader is referred to Section 4.2.

4.7.3.1 Particulate Emissions (Trace Elements)

In the assessment of FBC, the emissions of all trace elements were believed to be reduced below that for FGD because of lower temperature of combustion. This assumption needs to be verified. Questions to be answered include:

1. What are the partitioning factors for the elements?
2. What is the chemical form of the emitted element?
3. Is the deposition pattern of particulates emitted from FBC different from that of conventional combustion?

In addition, there are the following questions which relate to the assessment of impacts of emitted trace elements:

4. What is the potential for biomagnification of trace elements emitted by coal-fired power plants?
5. How do the various trace elements cycle through an ecosystem or between ecosystems (i.e., pathways)?

4.7.3.2 Solid Wastes

The following information is needed for an assessment of solid-waste emission environmental impacts:

1. The chemical forms of trace and major elements in the fly ash, bottom ash, and slag.
2. The extent of trace-element adsorption onto or within spent sorbent from FBC.
3. Effective fixatives for FGD sludge and procedures for dewatering.

4. Effectiveness of settling pond liners.
5. Methods to reduce seepage from ultimate disposal sites.
6. Effects on the growth, yield, and trace-element content of vegetation on soils treated with fly ash.
7. Successful reclamation procedures for fly ash and sludge settling ponds.
8. Environmental effects of fly ash utilization in roads and building materials.