



US Army Corps of Engineers
Construction Engineering Research Laboratory

USACERL TECHNICAL REPORT E-89/05
February 1989
Coal Use Technologies

AD-A206 949

Survey of Microcleaning Methods for Application to Army Coal-Fired Plants

by
Jeraldine Northrup
Cindy Jongkind
Gary Schanche

Many Army installations use coal-fired boilers in their physical plants. These facilities are now facing more rigorous enforcement of regulations governing air pollutant emissions, largely due to the increased concern over acid rain. Of particular significance to these plants is that new standards have lowered the acceptable level of sulfur oxides (SO_x) in the exhaust. Compliance with these regulations will have major economic impact on the plants' operating costs.

The U.S. Army Construction Engineering Research Laboratory (USACERL) is investigating emission control technologies to find the most cost-effective way of meeting the new standards for SO_x. Several options are available, including flue gas desulfurization, fluidized bed combustors, and precombustion cleaning. This report focuses on microcleaning—one form of precombustion treatment to remove SO_x and other particulates before the coal is burned, eliminating these byproducts from the emission.

Three types of microcleaning were evaluated: chemical, biological, and physical. Many of the chemical and biological processes are still in the early stages of development and have not been commercialized. In addition, all of the processes were found to be more expensive than flue gas desulfurization—an option used at many industrial plants.

As microcleaning technology emerges, it may become competitive with other control methods. Another consideration is that the emission regulations may eventually mandate use of precombustion cleaning to achieve the required emission quality. For the present, however, microcleaning technology is immature and does not represent the best alternative for the Army in reducing SO_x. (KT/RW) K

DTIC
ELECTE
APR 13 1989
S D
H

Approved for public release; distribution is unlimited.

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official indorsement or approval of the use of such commercial products. The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

***DESTROY THIS REPORT WHEN IT IS NO LONGER NEEDED
DO NOT RETURN IT TO THE ORIGINATOR***

SECURITY CLASSIFICATION OF THIS PAGE

| REPORT DOCUMENTATION PAGE | | | | Form Approved OMB No 0704 0188 Exp Date Jun 30 1986 | |
|--|-------|--|---|---|--------------------------------|
| 1a REPORT SECURITY CLASSIFICATION Unclassified | | 1b RESTRICTIVE MARKINGS | | | |
| 2a SECURITY CLASSIFICATION AUTHORITY | | 3 DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution is unlimited. | | | |
| 2b DECLASSIFICATION / DOWNGRADING SCHEDULE | | 5 MONITORING ORGANIZATION REPORT NUMBER(S) | | | |
| 4 PERFORMING ORGANIZATION REPORT NUMBER(S) USA-CERL E-89/05 | | 7a NAME OF MONITORING ORGANIZATION | | | |
| 6a NAME OF PERFORMING ORGANIZATION U.S. Army Construction Engr Research Laboratory | | 6b OFFICE SYMBOL (If applicable) CECER-ES | | 7b ADDRESS (City, State, and ZIP Code) | |
| 6c ADDRESS (City, State, and ZIP Code) P.O. Box 4005 Champaign, IL 61820-1305 | | 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER | | | |
| 8a NAME OF FUNDING / SPONSORING ORGANIZATION USAEHSC | | 8b OFFICE SYMBOL (If applicable) CEHSC-FU | | 10 SOURCE OF FUNDING NUMBERS | |
| 8c ADDRESS (City, State, and ZIP Code) Fort Belvoir, VA 22060 | | PROGRAM ELEMENT NO 4A162781 | PROJECT NO AT45 | TASK NO DO | WORK UNIT ACCESSION NO 006 |
| 11 TITLE (Include Security Classification) Survey of Microcleaning Methods for Application to Army Coal-Fired Plants (U) | | | | | |
| 12 PERSONAL AUTHOR(S) Northrup, Jeraldine; Jongkind, Cindy; Schanche, Gary | | | | | |
| 13a TYPE OF REPORT final | | 13b TIME COVERED FROM _____ TO _____ | | 14 DATE OF REPORT (Year, Month, Day) 1989, February | |
| 15 PAGE COUNT 36 | | | | | |
| 16 SUPPLEMENTARY NOTATION Copies are available from the National Technical Information Service Springfield, VA 22161 | | | | | |
| 17 COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) | | |
| FIELD | GROUP | SUB-GROUP | | | |
| 13 | 01 | | boilers microcleaning | | |
| 10 | 02 | | coal coal-fired plants | | |
| 19 ABSTRACT (Continue on reverse if necessary and identify by block number) | | | | | |
| <p>Many Army installations use coal-fired boilers in their physical plants. These facilities are now facing more rigorous enforcement of regulations governing air pollutant emissions, largely due to the increased concern over acid rain. Of particular significance to these plants is that the new standards have lowered the acceptable level of sulfur oxides (SO_x) in the exhaust. Compliance with these regulations will have major economic impact on the plants' operating costs.</p> <p>The U.S. Army Construction Engineering Research Laboratory (USACERL) is investigating emission control technologies to find the most cost-effective way of meeting the new standards for SO_x. Several options are available, including flue gas desulfurization, fluidized bed combustors, and precombustion cleaning. This report</p> <p style="text-align: right;">(Cont'd.)</p> | | | | | |
| 20 DISTRIBUTION / AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS | | | 21 ABSTRACT SECURITY CLASSIFICATION Unclassified | | |
| 22a NAME OF RESPONSIBLE INDIVIDUAL Dana Finney | | | 22b TELEPHONE (Include Area Code) (217) 352-6511 x 389 | | 22c OFFICE SYMBOL CECER-IMT |

Block 19. (Cont'd).

focuses on microcleaning--one form of precombustion treatment to remove SO_x and other particulates before the coal is burned, eliminating these byproducts from the emission.

Three types of microcleaning were evaluated: chemical, biological, and physical. Many of the chemical and biological processes are still in the early stages of development and have not been commercialized. In addition, all of the processes were found to be more expensive than flue gas desulfurization--an option used at many industrial plants.

As microcleaning technology emerges, it may become competitive with other control methods. Another consideration is that the emission regulations may eventually mandate use of precombustion cleaning to achieve the required emission quality. For the present, however, microcleaning technology is immature and does not represent the best alternative for the Army in reducing SO_x .

FOREWORD

This work was performed for the U.S. Army Engineering and Housing Support Center (USAEHSC) under Project 4A162781AT45, "Energy and Energy Conservation"; Work Unit DO-006, "Coal Use Technologies." The USAEHSC Technical Monitor was Bernard Wasserman, CEHSC-FU.

The research was conducted by the U.S. Army Construction Engineering Research Laboratory (USACERL) Energy Systems Division (ES). Dr. G.R. Williamson is Chief of ES. The technical editor was Dana Finney, USACERL Information Management Office.

COL Carl O. Magnell is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.



| | |
|--------------------|-------------------------------------|
| Accession For | |
| NTIS GRA&I | <input checked="" type="checkbox"/> |
| DTIC TAB | <input type="checkbox"/> |
| Unannounced | <input type="checkbox"/> |
| Justification | |
| By _____ | |
| Distribution/ | |
| Availability Codes | |
| Dist | Avail and/or Special |
| A-1 | |

CONTENTS

| | Page |
|---|------|
| DD FORM 1473 | 1 |
| FOREWORD | 3 |
| LIST OF TABLES AND FIGURES | 5 |
| 1 INTRODUCTION | 7 |
| Background | |
| Objective | |
| Approach | |
| Scope | |
| Mode of Technology Transfer | |
| 2 REGULATIONS AND THE COAL-CLEANING CONCEPT: OVERVIEW | 9 |
| Emission Regulations | |
| Coal Cleaning | |
| 3 MICROCLEANING PROCESS | 15 |
| Overview | |
| Advanced Coal-Cleaning Process | |
| 4 CHEMICAL MICROCLEANING | 19 |
| Gravimelt—Alkali Leaching | |
| General Electric Microwave Process | |
| 5 BIOLOGICAL MICROCLEANING | 22 |
| 6 PHYSICAL MICROCLEANING | 24 |
| Advanced Flotation | |
| True Liquid Beneficiation | |
| Electrostatic Separation | |
| High-Gradient Magnetic Separation | |
| Agglomeration | |
| 7 CONCLUSIONS AND RECOMMENDATIONS | 32 |
| METRIC CONVERSION FACTORS | 33 |
| REFERENCES | 34 |
| DISTRIBUTION | |

TABLES

| Number | | Page |
|--------|---|------|
| 1 | State Emission Standards | 10 |
| 2 | USEPA New Source Performance Standards for Sulfur Dioxide Emissions | 10 |
| 3 | Percentage Sulfur in Coal Needed To Meet Emission Standards | 11 |
| 4 | Summary of Physical Coal-Cleaning Benefits for Existing Boilers | 14 |
| 5 | Advanced Coal-Cleaning Processes and Their Developers | 17 |
| 6 | Estimated Capital Costs for a Gravimelt Plant vs. FGD | 20 |
| 7 | Summary of Costs for TRW Gravimelt Processed Coal | 20 |
| 8 | Summary of Costs for GE Microwave Process | 21 |
| 9 | Cleaning Results of the AFT Beneficiation Process | 26 |
| 10 | DOW Process Results (Integrated Plant) | 27 |
| 11 | AED Electrostatic Separation Process Results (Integrated Plant) | 28 |
| 12 | NRCC Oil Agglomeration Process Results | 29 |
| 13 | Typical Otisca T-Process Cleaning Results | 30 |
| 14 | Coal Microcleaning vs. Flue Gas Desulfurization: Cost Comparison | 32 |

FIGURE

| | | |
|---|-----------------------------------|----|
| 1 | Proposed Model of the Coal Matrix | 12 |
|---|-----------------------------------|----|

SURVEY OF MICROCLEANING METHODS FOR APPLICATION TO ARMY COAL-FIRED PLANTS

1 INTRODUCTION

Background

Coal is a plentiful resource in the United States; however, its use is limited due to ecological problems. Coal combustion produces particulates, sulfur oxides (SO_x), nitrogen oxides (NO_x), and other pollutants. Sulfur dioxide in particular has been linked to the acid rain situation, causing Congress to impose stricter regulations on emissions from coal-fired boilers. These regulations have had a major economic impact on coal-burning plants, including the large number operating at Army installations.

To meet emission standards, most Army coal-fired plants have been using some type of particulate control device, usually placed on the end of a boiler. SO_x controls are also available, but these devices are very expensive and often are not totally effective in removing SO_x . The Army currently controls SO_x by using low-sulfur coal. This type of coal can be more expensive than other varieties and restricts competition in purchase. In addition, even coal with the lowest natural sulfur content may not meet future air quality standards.

An alternative is to remove pollutants such as sulfur before burning the coal. While this technology is advanced enough to use at an industrial scale, it is also expensive. However, compared with the cost of emission control devices, it may represent a competitive technology. Also, it is possible that future emission standards will become so strict that precombustion cleaning is the only effective means of achieving the acceptable levels.

In anticipation of more stringent air quality regulations and higher oil prices, and to ensure energy independence, the Army and private industry are seeking methods of burning coal that will be both cost-effective and clean. Among the technologies being studied are flue gas desulfurization, slagging combustors, fluidized bed combustors, and precombustion cleaning. One type of precombustion cleaning, called "microcleaning," is emerging as a very promising method. Microcleaning involves the removal of sulfur and mineral matter from coal that has been pulverized to micron size. Later, when the coal is burned, these substances are not present and therefore do not appear in the emissions.

The U.S. Army Corps of Engineers (USACE) is responsible for overseeing the Army's physical plants. To find an economical alternative to emission control devices, the U.S. Army Engineering and Housing Support Agency of USACE has asked the U.S. Army Construction Engineering Research Laboratory (USACERL) to investigate the possibilities of using microcleaning techniques at industrial-scale boiler plants. To be practical, the technology would have to meet the following specifications:

1. Must consist of a group of equipment that could take run-of-mine high ash and high sulfur coal and refine it to a relatively low (less than 1 percent) sulfur content and low (less than 6 percent) ash content.
2. Must remove both organic and inorganic sulfur.

3. Must be designed to be operated easily by a technician at a typical industrial-scale boiler plant.

4. Should crush the coal and clean it using microcleaning technologies (such as magnetic separation).

5. Ideally, will not increase the coal cost to more than \$50/ton* (excluding transportation).

6. Should have a processing rate in the 1- to 15-ton/hr capacity range.

Objective

The objective of this work is to investigate state-of-the-art coal microcleaning technologies capable of economically reducing the ash and sulfur contents of coal prior to firing.

Approach

USACERL surveyed the literature to provide an overview of microcleaning methods already being used commercially or at an advanced developmental stage. The findings were analyzed to determine applicability to the Army's physical plant based on the above specifications. Recommendations were developed based on the results. To adjust the economics to FY88 dollars, all costs were scaled from their base year to present worth using the Maintenance and Supply (M&S) cost index of *Chemical Engineering*.¹

Scope

This report is intended to serve as a reference covering state-of-the-art coal microcleaning technologies available for use by Army installations. It describes how the technology works, the types of sulfur and mineral matter removed, and the relative costs of using the technology.

Mode of Technology Transfer

Information in this report will be summarized in an Engineer Technical Note covering coal combustion retrofit technologies.

* A metric conversion chart appears on p 33.

¹"Economic Indicators," *Chemical Engineering*, Vol 95, No. 6 (April 25, 1988), p 9.

2 REGULATIONS AND THE COAL-CLEANING CONCEPT: OVERVIEW

Emission Regulations

Although historically the major motivation for coal cleaning was to remove ash-forming minerals and other impurities, the emphasis now is on removing sulfur from the coal. The Clean Air Act of 1970 mandated that individual states set their own standards in compliance with the National Ambient Air Quality Standard (NAAQS). Each state is then regulated by its State Implementation Plan (SIP). The SIPs vary from state to state, and most distinguish between metropolitan and nonmetropolitan areas. Table 1 shows some examples of SIPs.²

Because the states could set their own limits under these provisions, new industries could be attracted by setting lenient emission standards. To discourage this competition between states, the U.S. Environmental Protection Agency (USEPA) established New Source Performance Standards (NSPS) for plants larger than 250 million Btu/hr and built between 1972 and 1978 (called "new" sources). NSPS sets a limit of 1.2 lb SO₂/10⁶ Btu produced. Steam generators falling under this standard are referred to as "new sources."

The 1977 Amendments to the Clean Air Act mandated the 1.2 lb SO₂/10⁶ Btu and also required a percentage reduction in potential sulfur dioxide emissions.² Table 2 lists these emission standards and Table 3 shows the percentage sulfur in coal required to meet the standards.³ These so-called "new-new sources" include coal fired steam generators larger than 250 million Btu/hr and built after 18 September 1978.

Units are classified as either existing sources, new sources, or new-new sources as defined above. It can be seen that the amount of sulfur removal required will depend on the size, location, and age of the unit. Most units for this study fall under "existing" sources and therefore have to comply with the SIP.

On 16 December 1987, the USEPA issued new rules for new or modified industrial boilers.⁴ This air pollution control standard requires sulfur dioxide emission reductions of 90 percent and a limit of 1.2 lb/10⁶ Btu heat input for boilers with a heat input of 100 million Btu/hr and above. For installations using an emerging technology, a 50 percent reduction with a limit of 0.6 lb/10⁶ Btu is required.

Coal Cleaning

"Coal cleaning," "coal preparation," and "coal beneficiation" are all terms used for operations performed on run-of-mine coal to clean or prepare it for a specific end use. Coal beneficiation removes sulfur and ash from coal by physical or chemical methods.

²E. H. Hall and G. E. Raines, "The Use of Coal Cleaning for Complying With SO₂ Emission Regulations," *Proceedings: Symposium on Coal Cleaning to Achieve Energy and Environmental Goals*, Vol I, S. E. Rogers and A. W. Lemmons, Jr. (Eds.), EPA 600/7-78-098a (U.S. Environmental Protection Agency [USEPA], April 1979).

³P. W. Spaite, et al., *Environmental Assessment of Coal Cleaning Processes: Technology Overview*, EPA 600/7-79-073a (USEPA, September 1979).

⁴*Federal Register*, Vol 52, No. 241 (16 December 1987), 40 CFR Part 60.

Table 1

State Emission Standards (lb SO₂/10⁶ Btu)

| State | Metropolitan Area | Nonmetropolitan Area |
|---------------|-------------------|----------------------|
| Alabama | 1.8 | 4.0 |
| Colorado | 0.2 | 0.2 |
| Illinois | 1.8 | 6.0 |
| Iowa | 5.0 | 5.0 |
| Kentucky | 1.2 | 5.7 |
| Ohio | 1.4 | 4.5 |
| Pennsylvania | 0.7 | 4.0 |
| West Virginia | 2.8 | 2.8 |

*Source: E. H. Hall and G. E. Raines, "The Use of Coal Cleaning for Complying With SO₂ Emission Regulations," *Proceedings: Symposium on Coal Cleaning to Achieve Energy and Environmental Goals*, Vol I, S. E. Rogers and A. W. Lemmons, Jr. (Eds.), EPA 600/7-78-098a (USEPA, April 1979).

Table 2

USEPA New Source Performance Standards for Sulfur Dioxides Emissions*

| SO ₂ Content of ROM** Coal (lb /10 ⁶ Btu) | SO ₂ Reduction Required |
|---|-------------------------------------|
| 0-2 | 70% |
| 2-6 | 0.6 lb/10 ⁶ Btu (70-90%) |
| 6-12 | 90% |
| >12 | to 1.2 lb/10 ⁶ Btu |

*Source: P. W. Spaite, et al., *Environmental Assessment of Coal Cleaning Processes: Technology Overview*, EPA 600/7-79-073a (USEPA, September 1979).

**ROM = run-of-mine.

Table 3

Percentage Sulfur in Coal Needed To Meet Emission Standards

| Emission Standard ^d (lb/SO ₂ /10 ⁶ Btu) | Btu/lb | | | |
|---|--------------------|--------|--------|--------|
| | 8000 | 10,000 | 12,000 | 14,000 |
| | Sulfur in Coal (%) | | | |
| 0.6 | 0.24 | 0.30 | 0.36 | 0.42 |
| 1.2 | 0.48 | 0.60 | 0.72 | 0.85 |
| 3.0 | 0.80 | 1.00 | 1.20 | 1.40 |
| 4.0 | 1.60 | 2.00 | 2.40 | 2.80 |
| 6.0 | 2.40 | 3.00 | 3.60 | 4.20 |

Physical methods rely on differences in size, shape, surface characteristics, and specific gravity of particles. They work without chemically modifying the coal matrix or mineral matter. Chemical methods, on the other hand, rely on chemical reactions between the reagent and the sulfur form. At present, physical methods are more developed than chemical techniques. Conventional physical coal-cleaning processes can remove from 20 to 50 percent of the sulfur.⁵ Chemical coal-cleaning methods can remove from 50 percent to more than 90 percent of the sulfur; however, most of these methods are still in developmental stages.

To appreciate how coal cleaning works, it is necessary to understand the basic composition of the coal matrix. Sulfur dioxide emissions are the result of three general forms of sulfur found in coal: organic, pyritic, and sulfate. Sulfate sulfur, present in the smallest amount, is usually water-soluble and can be removed by washing the coal, so it poses no major problems. Pyritic sulfur generally occurs as pyrite or marcasite. These two minerals have the same chemical composition (FeS₂), but different crystalline forms. Sulfide sulfur occurs as individual particles (0.1 micron to 25 cm in diameter) distributed throughout the coal matrix.⁶ Pyrite is a dense mineral compared with bituminous coal and is water-insoluble; thus, one of the most common methods of pyrite removal is by specific gravity separation. Pyritic sulfur is generally removed from coal by physical methods.

Organic sulfur is chemically bound to the organic structure of the coal and cannot be removed unless the chemical bonds are broken. Organic sulfur is generally believed to exist as thiophenes, sulfides, disulfides, and in heterocyclic ring compounds.⁷ Figure 1 shows a model of the coal matrix proposed by Given,⁸ where the difficulty of selectively breaking carbon-sulfur bonds while leaving the rest of the matrix intact can be seen. Organic sulfur must be removed from the coal matrix by chemical methods. The amount of organic sulfur represents the lowest limit to which coal can now be cleaned economically.

⁵J. D. Kilgroe et al., *Coal Cleaning Options for SO₂ Emission Reduction*, EPA/600/D-85/057 (USEPA, March 1985), p 1.

⁶D. L. Koury (Ed.), *Coal Cleaning Technology* (Noyes Data Corp., 1981), p 8.

⁷R. A. Meyers, *Coal Desulfurization* (Marcel Dekker, 1977), p 18.

⁸P. H. Given, *Fuel*, Vol 39, No. 147 (1960).

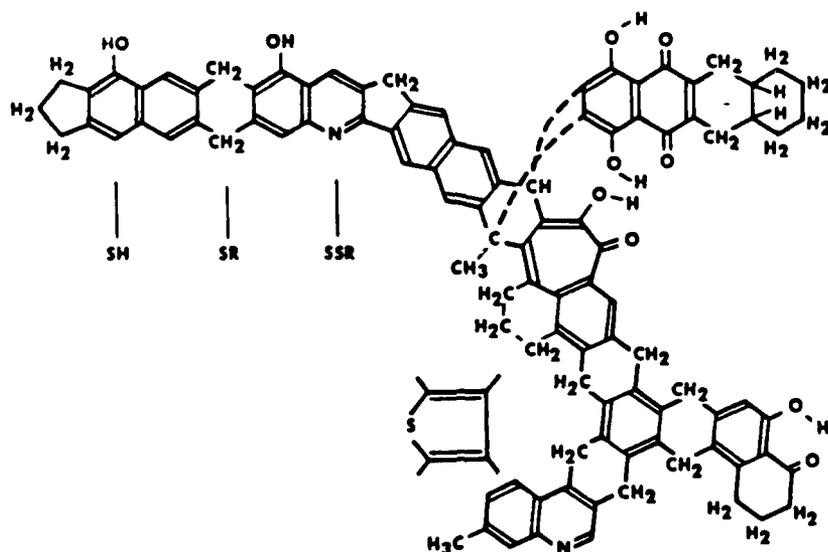


Figure 1. Proposed model of the coal matrix. (Source: P. H. Given, *Fuel*, Vol 39, No. 147 [1960]. Used with permission.)

The amount of sulfur present in coal along with the ratio of pyrite to organic sulfur can vary considerably in the three major regions of the U.S. coal reserves. The Western coal region generally has a low amount of sulfur. It is usually less than 1 percent and composed mostly of organic sulfur. The Interior Basin coal region has roughly 4 percent total sulfur of which 30 to 40 percent is organic. The Appalachian coal region, which supplies more than 60 percent of current U.S. coal production, has total sulfur ranges from 1 to 4 percent, with the organic sulfur ranging from 0.5 to 1 percent.⁹

The extent and kind of coal cleaning used will depend on the type of sulfur in the coal and, consequently, where the coal is mined. For some Appalachian coals, which are lowest in organic sulfur, physical coal cleaning alone may produce a low-sulfur cleaned coal.

Besides the obvious benefit of sulfur dioxide reduction, coal cleaning has other advantages, which can be classified into three categories: emissions reduction, material handling, and coal combustion. These benefits are summarized below.

Emissions Reduction

Conventional coal-cleaning processes can remove from 20 to 50 percent of the sulfur from high-sulfur coals. This reduction may help an existing source in meeting its SIP or even new sources by meeting the 1.2 lb SO₂/10⁶ Btu limit. For example, if the SIP for a given state is decreased from 6 lb SO₂/10⁶ Btu to 4.5 lb SO₂/10⁶ Btu, coal cleaning would be the most economical choice.

Coal cleaning can be used in combination with flue gas desulfurization (FGD) when coal cleaning alone cannot produce clean enough coal. Coal cleaning with FGD can significantly reduce the volume of limestone consumed and sludge disposal costs. Also,

⁹R. A. Meyers, p 5.

the FGD system can be designed so that, when clean coal is burned, only a portion of the flue gas stream is processed.¹⁰ The remainder is bypassed, alleviating the need for plume reheating and its associated costs. Coal cleaning could reduce the size of FGD systems needed up to 70 percent with a proportional savings in capital cost.¹¹

Advanced fine coal-cleaning processes that can remove 90 percent sulfur could be used for new-new sources if they become more cost-effective than FGD.

Materials Handling

When coal is cleaned at the mine, transportation costs are lowered since the cleaned coal has less ash and consequently a higher Btu value for a given weight. Ash handling and ash disposal costs at the plant are also reduced since the burned coal has a lower total ash content.

Provisions of the 1978 United Mine Workers (UMW) contract require payment by the mine operator of \$2.10 to the UMW Pension and Benefit Trust Fund for each ton of coal shipped to the consumer. Thus, if coal is cleaned at the mine, for the same Btu value, less coal will be shipped, resulting in a lower cost per Btu for the consumer.¹²

Coal Combustion

Coal cleaning lowers the mineral ash of coal, thereby reducing the associated ash problems. For example, slagging, fouling, and corrosion are reduced, which lowers the cost of boiler operation and maintenance and requires less downtime. Also, cleaned coal is much more uniform in Btu value and size, thus improving downstream fuel operations.

Because the cleaned coal has a higher heating value, chances of derating the boiler due to deteriorating coal quality are reduced. Also, a lower potential for slagging would allow the furnace to be designed with higher heat transfer rates and smaller furnace volumes, which results in increased efficiency.

Although cost benefits due to improved boiler operations are difficult to determine, one study has estimated savings of \$2.76/ton of cleaned coal, with ranges of \$0.53/ton to \$8.48/ton.¹³ Another study has shown a typical cost benefit of \$10.92/ton of cleaned coal. Table 4 shows the breakdown and high/low range.

¹⁰P. S. Barr, "Coal Cleaning to Improve Boiler Performance and Reduce SO₂ Emissions," *Power*, Vol 125, No. 9 (September 1981), p S-3.

¹¹*Use of Coal Cleaning in Bubbles Trade-Offs and Acid Rain Legislation*, Proceedings: First Annual Pittsburgh Coal Conference (U.S. Department of Energy, September 1984), p 374.

¹²D. L. Koury (Ed.), p 347.

¹³J. D. Kilgroe, et al., p 13.

Table 4

**Summary of Physical Coal-Cleaning Benefits
for Existing Boilers***

| Benefit Area | Cost of Cleaned Coal (\$/ton) | |
|-----------------------------|-------------------------------|--------------|
| | Typical | Range |
| Coal and ash handling | | |
| Transportation | 1.06 | 0.02 - 2.27 |
| Handling and storage | ** | *** |
| Pulverizers | 0.00 | 0.00 - 6.82 |
| Ash collection and handling | ** | 0.00 - 0.38 |
| Ash disposal | 0.10 | 0.00 - 0.38 |
| Boiler operation | | |
| O&M | 0.61 | 0.15 - 3.03 |
| Availability | 2.88 | 0.45 - 7.76 |
| Efficiency | 0.15 | 0.08 0.38 |
| Capacity | 0.00 | 0.00 13.65 |
| Gas cleaning | | |
| Particulate control | ** | ** |
| FGD systems | 6.07 | 0.00 - 16.68 |
| Total | 10.92 | |

*Source: P. J. Phillips and R. M. Cole, "Economic Penalties Attributable to Ash Content of Steam Coals," paper presented at the American Institute of Mining Engineers (AIME) Annual Meeting, New Orleans (February 1979). Used with permission.

**Insignificant for existing plants.

***Not determined.

3 MICROCLEANING PROCESS

Overview

Microcleaning is also called "fine coal cleaning." In terms of desulfurization, small particle size optimizes the amount of sulfur removed. For chemical methods, fine-grinding provides more surface area for allowing reactions to occur. For physical methods, the pyritic sulfur needs to be liberated from the coal matrix. Sulfide sulfur occurs as veins or individual particles that can be finely disseminated throughout the coal matrix. To maximize desulfurization, the pyrite has to be liberated from the coal matrix by grinding the coal to a small particle size.¹⁴ However, at these small particle sizes, conventional coal-cleaning methods become inefficient and cannot make the necessary separation.

To improve the performance of coal-cleaning methods, extensive research and development are being conducted on fine coal cleaning. This activity has increased for two reasons. First, there is a growing interest in producing an ultraclean fuel to use directly in gas turbines or as a substitute for FGD. Second, coal fines constitute a large percentage of coal preparation plant feed and refuse. Modern mining techniques, including the increased use of continuous miners and longwall shearers, have increased the proportion of coal fines as preparation plant feed.¹⁵ To take advantage of these coal fines, increased crushing within the plant itself will facilitate ash and sulfur removal.

Physical coal cleaning is not a one-unit operation, but a series of steps. The primary coal operations are comminution, sizing, cleaning, and dewatering. Coal is crushed and divided into three size fractions: coarse (-1-1/2 to 3/8 in.), medium (-3/8 in. to 28 mesh), and fine (-28 mesh to 100 mesh). Each size fraction is cleaned by the processes best suited to its size. Very fine coal of less than 100 mesh is seldom processed in commercial plants due to inefficient methods of cleaning this fine-sized coal. The disproportionately large quantity of surface moisture entrained within the fine coal makes processing very costly. Thus, 20 years ago, the relatively low cost of coal made it uneconomical to process these fines. Today, however, there is an attempt to find ways to recover their Btu value.¹⁶ Improvements in froth flotation, agglomeration techniques, and magnetic separation have shown promising results; however, these advanced coal-cleaning processes are more expensive than conventional methods.

Because of the small particle size needed for fine-cleaning, microcleaned coal must be further processed. Several options are available. The coal can be processed for coal slurry applications, dried for use in a pulverized coal-firing unit, or pelletized for use in stoker-fired furnaces. Coal-water slurry is still a developing technology. Advances would create a market for products of fine coal-cleaning processes.

¹⁴Y. A. Attia, *Processing and Utilization of High-Sulfur Coals* (Elsevier, 1985), p 267.

¹⁵J. Burger, "Three New Approaches to the Problem of Dewatering Fine Coal," *Coal Age*, Vol 21, No. 1 (January 1986).

¹⁶A. C. Wright, "Collecting Fines for New Markets," *Coal Age*, Vol 90, No. 1 (January 1985), pp 57-64.

Tests in laboratory-scale reactors have demonstrated that incorporating calcium-bearing minerals into coal can produce a fuel pellet that retains a significant fraction of the remaining sulfur. Thus, pelletizing produces a fuel that can be fired in unmodified stokers in addition to further reducing the SO₂ emissions.¹⁷

An economic alternative to micronizing 100 percent of the feed coal is to use a multistream processing unit in which two streams are produced: a middlings product of medium sulfur content and a fine coal product with low sulfur. This procedure has been demonstrated at the Coal Cleaning Test Facilities (CCTF) near the Homer City, PA, power-generating plant.¹⁸ A medium-sulfur coal was produced for two 600-MW generating units which were existing sources and had to meet a 4.0 lb SO₂/10⁶ Btu level. The low-sulfur coal was used for a new source, a 650-MW unit required to achieve the 1.2 lb SO₂/10⁶ Btu emission limit.

Advanced Coal-Cleaning Process

The only microcleaning processes that could meet the required 1 percent sulfur and 6 percent ash are the chemical methods. TRW's Gravimelt is the most advanced of the chemical processes, but its commercialization is not expected until after 1995.¹⁹

Table 5 lists major advanced coal-cleaning processes and the organizations involved in their development.²⁰ It also provides information on the sulfur removal method, the types of sulfur removed, and the relative time period before the method can be commercialized. Processes with commercialization scheduled for the near future are all physical methods that can remove only the pyritic sulfur. The chemical processes require long-term development before they can be used effectively.

¹⁷A. C. Wright.

¹⁸D. L. Koury (Ed.), p 30.

¹⁹D. A. Horazak, et al., *Gas Turbine Systems Research and Development Program* (U.S. Department of Energy, February 1986), p 5-7.

²⁰J. D. Kilgroe, et al., p I-40.

Table 5

Advanced Coal-Cleaning Processes and Their Developers

Chemical Methods

Process : Alkali leaching
 Major Developers : "Gravimelt," TRW, Inc.
 Cleaning Methods : Removal of sulfur by molten alkali hydroxides.
 Removal of ash by weak acid leaching.
 Type of Sulfur Removed : Pyritic and organic
 Commercialization Status : L*

Process : Microwave
 Major Developers : General Electric, Inc.; TRW
 Cleaning Methods : Microwave irradiation of NaOH treated coal.
 Washing to remove soluble sulfur compounds.
 Type of Sulfur Removed : Pyritic and organic
 Commercialization Status : L

Process : Biological
 Major Developers : Ohio State U., Lehigh, Penn State,
 Atlantic Research Corp.
 Cleaning Method : Bacteria selectively oxidize mineral
 sulfur and some organic sulfur.
 Type of Sulfur Removed : Pyritic and organic
 Commercialization Status : L

Physical Methods

Process : Advanced flotation
 Major Developers : U.S. Dept. of Energy, Penn State U.,
 Advanced Fuels Technology
 Cleaning Methods : Coal and/or ash are floated in cells
 using micro-bubbles or improved reagents.
 Type of Sulfur Removed : Pyritic
 Commercialization Status : N, I

Process : True (or homogeneous) liquid beneficiation
 Major Developers : Otisca Industries, Dow Chemical,
 TRW, American Electric Power
 Cleaning Methods : Gravimetric separation using organic
 fluids or brines.
 Type of Sulfur Removed : Pyritic
 Commercialization Status : N, I

Table 5 (Cont'd.)

| | | |
|--------------------------|---|--|
| Process | : | Electrostatic Separation |
| Major Developers | : | Advanced Energy Dynamics |
| Cleaning Methods | : | Electrostatic drum separator for very fine particles. Proprietary for separation of ultrafines. |
| Type of Sulfur Removed | : | Pyritic |
| Commercialization Status | : | N, I |
| | | |
| Process | : | High-gradient magnetic separation |
| Major Developers | : | Sala Magnetics, Magnetic Corp. of America, Tennessee Valley Authority (TVA) |
| Cleaning Methods | : | Separation of paramagnetic mineral particles in a high-intensity magnetic field. |
| Type of Sulfur Removed | : | Pyritic |
| Commercialization Status | : | N, I |
| | | |
| Process | : | Agglomeration |
| Major Developers | : | National Research Council of Canada, Otisca Industries, Battelle Columbus, University of Pittsburgh |
| Cleaning Methods | : | Form agglomerates of coal in oils, organic liquids, CO ₂ (liq.). Size separation of agglomerates from fine mineral particles. |
| Type of Sulfur Removed | : | Pyritic |
| Commercialization Status | : | N, I |

*N = Near-term potential; could be commercial by 1990. I = Intermediate-term potential; could be commercial by 1995. L = Long-term potential (not available for commercialization until after 1995).

4 CHEMICAL MICROCLEANING

To remove the organic sulfur in coal, chemical processes must be used. Part of the difficulty in finding a successful process is that the chemical reagent must selectively break sulfur-carbon bonds while leaving the remaining coal matrix relatively unaffected. The reagent should also be regenerable and inexpensive.

A recent survey²¹ found 12 chemical coal preparation processes currently under investigation. Most of these processes involve only sulfur removal. However, two methods, TRW's Gravimelt and General Electric's Microwave, also remove a considerable amount of ash and are described below.

Gravimelt—Alkali Leaching

TRW's Gravimelt process is the most advanced of the chemical processes. A series of leaching steps at elevated temperatures remove almost all of the sulfur and mineral matter. The product could be processed for a coal-water mixture or as crushed coal for pulverized coal firing.

The TRW Gravimelt process involves the treatment of coal with molten sodium hydroxide or mixtures of sodium and potassium hydroxides at temperatures of 617 to 707° F to chemically extract organic and pyritic sulfur and the coal mineral matter into the molten alkali. The high density of the caustic melt causes the lightweight purified coal to float to the surface where it is skimmed off and washed with water to remove residual caustic, which is then recycled after concentration. The coal is next washed with dilute acid to recover the last remaining alkali and form a product slurry that can either be processed into a coal-water mixture or filtered from the wash solution for use as a solid fuel. Spent alkali containing coal-derived sulfur and mineral matter is treated to recover the coal minerals and the sodium and potassium sulfides. The sodium and potassium sulfides are converted to an elemental sulfur product and combined with sodium and potassium hydroxide which is recycled to the reactor. The acid wash solution is also treated to recover the sodium and potassium values for recycle to the reactor.

The Gravimelt process can produce coal that could be used as a fuel for turbine or diesel engines or as utility or industrial boiler feed. Table 6 compares the Gravimelt cost with that of FGD for a new utility plant.²² The physical size of the utility boiler would be considerably smaller than normal due to reduced ash-handling needs.

For industrial boilers where the per kilowatt cost of scrubbing is relatively high (often two or three times the amount shown in Table 6 for FGD), a central Gravimelt plant serving many smaller boiler plants could prove very economical. Gravimelt coal could be transported as a liquid coal-water mixture or as a solid powder in closed railway cars. Table 7 summarizes the reported costs for coal processed in this way.

²¹P.C. Merritt, "Advanced Coal Cleaning Processes Sought for Superclean Coal," *Coal Age* (June 1986).

²²R. A. Meyers, "Gravimelt Process Applications and Economics," *Proceedings of the First Annual Pittsburgh Coal Conference* (DOE, September 1984).

Table 6

Estimated Capital Costs for a Gravimelt Plant vs. FGD
for New 500-MW Baseload Utility

| Section | Gravimelt- Fueled Utility, \$ x 10 ⁶ | Coal-Fueled Utility, \$ x 10 ⁶ (\$/KW Nameplate) |
|---------------------------------|---|---|
| Power plant less FGD and ESP | 353* | 441 (882) |
| ESP | ** | 36 (72) |
| FGD | - | 132 (265) |
| Gravimelt plant | 125*** | - |
| Total | 478 | 609 (1219) |

*A 10 percent cost savings for oil-fired utility vs. coal utility.

**If NSPS standard of 0.03 lb particulates emissions/10⁶ Btu is met by Gravimelt combustion, no ESP is needed.

***Based on Department of Energy (DOE) sponsored Engineering Societies Commission on Energy, Gravimelt plant capital cost estimate was \$278 x 10⁶ for a 3.3 x 10⁶ ton/yr plant. Also, a utility heat rate of 10,000 Btu/KWh with baseload utility operating 85 percent online was assumed.

Table 7

Summary of Costs for TRW Gravimelt Processed Coal*

| Item | Cost (\$) |
|--|-----------|
| O&M | 23.2 M |
| Capital charges | 53.8 M |
| Total annual costs | 77.0 M |
| Physical coal cleaning/ton | 4.6 |
| O&M costs/ton of coal | 7.1 |
| Capital charges/ton of coal | 16.3 |
| Processing costs/ton of coal (excluding fuel costs) | 28.0 |
| Fuel costs/ton of coal | 49.4 |
| Total costs /ton of clean coal | 77.4 |

*Source: D. Boron and R. Kollack, "Prospects for Chemical Coal Cleaning," *Mining Engineering*, Vol 8, No. 2 (February 1986). Used with permission.

General Electric Microwave Process

The carbon and hydrogen in coal are relatively unaffected by microwave radiation. However, water, caustic, pyrite, and other mineral matter components are strong conductors of microwave radiation energy at the proper frequency. As a result, selective heating of the noncarbonaceous materials occurs, enabling the chemical reaction of sulfur and ash with caustic. Although very high temperatures may result from localized heating, most of the coal remains near 572 °F due to limited conductive heat transfer.

As with the Gravimelt process, the coal sulfur and ash are substantially removed, leaving the hydrocarbon structure of the coal relatively unaffected. The reacted coal sulfur is converted to alkali sulfides and polysulfides, while the mineral matter is apparently converted to alkali-aluminum-silicates and other byproducts that are water- and acid-soluble.

In the Microwave process, 30 mesh by 0 physically beneficiated coal is mixed with aqueous sodium hydroxide and dried to about 20 percent moisture so that the coal-to-caustic weight ratio ranges from 0.25:1 to 7.0:1. The mixture of coal and caustic is then exposed to microwave irradiation in multiple treatments of 25 to 45 sec each.

The coal product from the microwave reactor is water-washed to remove reacted sulfur products, unreacted sodium hydroxide, and other reaction byproducts. The coal is filtered and washed with a dilute acid solution to remove reacted mineral matter. The acid-washed coal is then filtered and water-washed to remove residual acid and acid byproducts. Table 8 summarizes costs for the GE Microwave process.

Table 8
Summary of Costs for GE Microwave Process*

| Item | Cost (\$) |
|--|-----------|
| O&M | 28.7 M |
| Capital charges | 69.6 M |
| Total annual costs | 98.3 M |
| Physical coal cleaning | 5.45 |
| O&M/ton of coal | 8.69 |
| Capital charges/ton of coal | 21.16 |
| Processing costs/ton of coal (excluding fuel costs) | 35.30 |
| Fuel costs/ton of coal | 52.47 |
| Total costs/ton of clean coal | 87.77 |

*Source: D. Boron and R. Kollack, "Prospects for Chemical Coal Cleaning," *Mining Engineering*, Vol 8, No. 2 (February 1986). Used with permission.

5 BIOLOGICAL MICROCLEANING

In the 1940s, an investigation of acid runoff from coal storage piles led to the discovery that microorganisms were oxidizing the coal-sulfur minerals. The oxidation process used oxygen from the air to provide metabolic energy. Carbon dioxide from the air provided carbon for growth and reproduction. These microorganisms were converting the water-insoluble sulfur forms to water-soluble sulfuric acid. These acids were being leached by rain, causing contamination to neighboring property and groundwater.

Although initial efforts were to find ways to inhibit the microorganisms and prevent acid runoff, the recent focus has been to isolate them for use in controlled experiments. The trend now is in researching the commercial possibilities of microbial desulfurization. The microorganisms used in this research consist mainly of the bacteria *Sulfolobus acidocaldarius* and *Thiobacillus ferrooxidans*. Of the two forms of sulfur found in coal--organic and inorganic--the *Sulfolobus* bacteria have been reported to remove the organic sulfur. The *Thiobacillus* remove the inorganic sulfur. Two processes involving the bacteria are "bioleaching" and "bioconditioning." In bioleaching, the bacteria are mixed with the coal until the sulfur compounds are oxidized and all of the sulfur is leached out. Bioconditioning is used to augment the flotation process; the bacteria are used to modify only the surface of the sulfur particle.

In bioleaching, the rates at which these microorganisms desulfurize coal will depend largely on the particular coal characteristics and process conditions, so it is not surprising that research results have differed. It does, however, make interpretation of the results difficult. Researchers at Ohio State University (OSU) reported that *Sulfolobus acidocaldarius* removed 75 percent of the total sulfur in 3 to 6 days.²³ Both organic and inorganic sulfur removal was reported.

Researchers at the University of Illinois have questioned these results. In an effort to duplicate the results of the OSU group, they tested the same strain of bacteria on Illinois coal and found no desulfurization.²⁴ Furthermore, they reported that *Sulfolobus acidocaldarius* is a heterotrophic organism and thus cannot significantly decrease the inorganic sulfur content of coal.

The *Thiobacillus* bacteria have given more consistent results in the desulfurization of inorganic sulfur. Researchers in England reported 90 percent removal in 10 days.²⁵ At the University of Illinois, 89.6 percent of the inorganic sulfur was removed in 27 days.²⁶

To use these bacteria in designing commercial desulfurization plants, many parameters have to be specified. Temperature, pressure, mixing, microbial nutrients, and air supply all must be optimized for efficient process reactions. The microbes need a

²³J. Murphy, et al., "Coal Desulfurization by Microbial Processing," paper presented at the First International Conference on Processing and Utilization of High Sulfur Coals, Ohio State University (October 1985).

²⁴J. B. Risatti and K. W. Miller, "Rates of Microbial Removal of Organic and Inorganic Sulfur From Illinois Coals and Coal Chars," paper presented at the Illinois Coal Development Board Fourth Annual Contractors' meeting, Urbana, IL (September 1986).

²⁵G. F. Andrews and J. Maczuga, "Bacterial Removal of Pyrite From Coal," *Fuel*, Vol 63 (March 1984), pp 297-302.

²⁶J. B. Risatti and K. W. Miller.

large surface area of coal and a moist environment, making the microbial process ideal for coal-water slurry applications.

In the process, the coal is finely crushed and then slurried in an aqueous medium having a low pH. This mixture is then inoculated with the bacteria, stirred, and aerated. After a predetermined time, the coal is washed, then either processed for coal-water slurry application or dried for use in pulverized-coal burners.

To test its design, the Atlantic Research Corporation has built a 2500-lb/day continuous pilot-scale microbial desulfurization system. This company has genetically engineered an organism, called "CB1," that oxidizes thiophenic (organic) sulfur compounds. The proposed process uses conventional techniques to reduce the inorganic sulfur content, then uses its bioreactor and CB1 to reduce the organic sulfur content. This process reportedly has removed up to 57 percent of the organic sulfur and averages about 37 percent. None of the ash is removed; however, energy recovery is 100 percent.

One of the greatest benefits of microbial desulfurization is its low cost. Atlantic Research reports that the entire process costs \$27.02/ton for a dry pulverized-coal product (dewatered to 10 percent moisture) or \$23.21/ton for selling to a coal-water slurry manufacturer (dewatered to 30 percent moisture). Other groups report costs as low as \$10.60 to 14.84/ton.²⁷

An alternative to bioleaching is to use the microbes for biosurface modification in flotation processes. Flotation separation processes take advantage of the difference in surface characteristics between coal and pyrite. While bioleaching must oxidize the whole pyrite particle and takes days, only 15 to 30 min are needed to change the surface characteristics of the pyrite particle.²⁸

Microbial desulfurization is a promising alternative because it has low capital and operating costs and is also less energy-intensive than conventional desulfurizing processes.

²⁷J. Murphy, et al.

²⁸Y. A. Attia and M. A. Elezsky, "Biosurface Modification in the Separation of Pyrite From Coal by Froth Flotation," paper presented at the First International Conference on Processing and Utilization of High Sulfur Coals, Ohio State University (October 1985).

6 PHYSICAL MICROCLEANING

Physical coal-cleaning processes use either the difference in surface characteristics or specific gravity between the coal matrix and the mineral particles. These processes are limited to the removal of pyrite sulfur. Nevertheless, depending on the percentage of pyritic sulfur contained in the feedstock coal, conventional physical cleaning technologies have a proven track record for effectively removing 20 to 60 percent of total sulfur at very low processing costs.

The Tennessee Valley Authority (TVA) has successfully reduced its cost of controlling SO_x by combining postcombustion flue gas desulfurization equipment with precombustion coal preparation. The methods used to prepare the coal prior to combustion are: dense medium (magnetite slurry) baths for coarse coals (3 by 3/8 in.); dense medium cyclones for intermediate coals (3/8 in. by 28 mesh); and single-stage froth flotation cells for fine coals (28 mesh by 0). Using this approach, TVA has reduced SO_x control costs by as much as 22.6 percent. The combination of conventional cleaning with FGD has been so successful that TVA has produced a computer model to optimize the process based on coal quality and boiler operating conditions.²⁹

Advanced Flotation

Flotation processes use the differences in surface characteristics and specific gravity between coal (1.3 g/cc bituminous coal) and pyrite (4.5 g/cc) to promote separation. Coal particles are covered with a reagent that makes the coal hydrophobic (water-repellent). Air bubbles are passed through a coal/water mixture and selectively adhere to the coal particles which then float to the surface. The mineral matter is wetted by the water and sinks to the bottom.

The chemical process of bubble adhesion can be selectively modified by adding certain reagents. These reagents either enhance the floating characteristics of coal or the wetting properties (water attraction) of the waste material. Reagents are also used to stabilize the froth, thus allowing enough time to remove the floated coal. One of the most important parameters in flotation chemistry is the surface characteristics of the coal particle. Since oxidized coal inhibits the flotation process, fine-grinding is often done in the water.

U.S. Department of Energy (DOE) Process

The DOE's Coal Preparation Division at the Pittsburgh Energy Technology Center is researching fine-grinding with flotation processes. DOE has concluded that to optimize beneficiation of micronized coal, a combination of a coarse coal cleaning, followed by wet grinding and recleaning by second-stage coal flotation is required.³⁰ Using this technique, an Upper Freeport coal sample was cleaned from 26 percent ash and 1.1

²⁹C. R. Wright, L. Larkin, F. M. Kennedy, and T. W. Tarkington, *Computer Economics of Physical Coal Cleaning and Flue Gas Desulfurization*, EPA-600/7-85-039 (USEPA, September 1985).

³⁰K. G. Miller, "Fine Grinding and Flotation to Desulfurize Coal," paper presented at the First International Conference on Processing and Utilization of High Sulfur Coals, Ohio State University (October 1985).

percent pyritic sulfur to 4.5 percent ash and 0.1 percent pyritic sulfur. Estimated cost for this process is \$9.81/ton.³¹

Illinois State Geological Survey (ISGS) Aggregate Flotation

The ISGS is promoting a fine coal-cleaning process claimed to recover 80 percent of the Btu value and to reject 80 to 90 percent of the sulfur-bearing and ash-forming minerals. The process is much like conventional flotation techniques. It involves the selective flotation and separation of very fine-sized coal (90 percent passing through 400 mesh) via formation of oil-coated coal-air bubbles.

A 10- to 30-lb continuous model unit has been tested and found successful. The testing focused on optimizing procedures and finding cost-effective reagents. One advantage of the aggregate flotation process over other ultrafine coal-cleaning methods is that old flotation cells can be retrofitted for the process. This modification avoids a capital investment for new cells.

Because of the ultrafine size of the coal, the product must either be pelletized or made into a coal-water slurry. The reagents for the ISGS process are proprietary. At present, the cost for the final product is said to be \$36.29/ton as a coal-water slurry supply.

Advanced Fuels Technology (AFT)—Beneficiation

The AFT beneficiation process is similar to froth flotation but uses different chemicals and a new tank design. The coal slurry and reagents are sprayed through a nozzle onto the tank surface. This technique is used to promote separation of flocculents of coal and mineral matter. Rather than having coal particles carried to the surface by air bubbles, aeration is forced by spraying. Table 9 lists a sample of some cleaning results reported for the AFT beneficiation process.³³

True Liquid Beneficiation

True liquid beneficiation is a gravimetric separation method that uses organic fluids or brines. When a coal-water slurry is mixed with the liquid, the coal particles have an affinity for the solvent phase and transfer to it. A liquid-liquid type of extraction occurs. For this study, only one true liquid beneficiation process was investigated--the Dow True Heavy Liquid Separation process.

The Dow process³⁴ uses two beneficiation steps to clean coal: (1) a liquid-liquid partitioning step for the -100-mesh coal fraction and (2) cyclone separation steps for all sizes of coal. The liquid-liquid partitioning step is used to remove clay from coal fines.

³¹T. W. Tarkington, F. M. Kennedy, and J. G. Patterson, *Evaluation of Physical/Chemical Coal Cleaning and Flue Gas Desulfurization*, EPA-600/7-79-250 (USEPA, November 1979).

³³L. E. Burgess, et al., "The AFT Beneficiation System: A New Way to Clean Coal," paper presented at the Fifth International Symposium on Coal Slurry Combustion and Technology, Tampa, FL (April 1983).

³⁴R. P. Killmeyer, "Selective Agglomeration: Let's Compare the Emerging Processes," *Coal Mining* (September 1985), pp 45-49.

Table 9
Cleaning Results of the AFT Beneficiation Process*

| | Ash (%) | | Sulfur (%) | | Product Recovery (%) |
|----------------------|---------|-------|------------|-------|----------------------|
| | Before | After | Before | After | |
| Alton (Utah) | 20.6 | 8.2 | 1.2 | 1.2 | 92.2 |
| Middle Kittanning | 12.6 | 5.7 | 4.2 | 2.3 | 96.0 |
| Pittsburgh | 6.5 | 3.6 | 0.4 | 0.3 | 91.2 |
| Pocohontas No. 2 | 6.0 | 1.8 | 0.6 | 0.6 | 92.3 |
| Taggart No. 2 | 3.5 | 0.6 | 0.6 | 0.5 | 83.6 |
| Wells Blend (ROM) | 38.1 | 6.6 | 0.9 | 0.7 | 94.0 |
| Wellmore No. 8 (ROM) | 48.7 | 4.9 | 0.4 | 0.7 | 98.3 |

*The AFT beneficiation process has costs similar to other flotation processes.

The process is done using water and a chlorinated solvent such as perchloroethylene or methylene chloride. The hydrophobic coal-rich particles collect in the heavier chlorinated solvent phase. This step only separates hydrophilic particles from those which are hydrophobic.

In the cyclone separation step, coal-rich particles from the liquid-liquid partition step (-100-mesh) and the coarser coal fractions (28 by 100 mesh) are slurried with solvent and pumped under pressure into cyclones. The product and refuse streams pass through a series of solvent removal/recovery steps.

The Dow process has a leveled cleaning cost of \$13.24/ton of cleaned coal. Cleaning results for the Dow process are reported in Table 10.

Electrostatic Separation

Advanced Energy Dynamics' electrostatic separation process takes advantage of the electrostatic differences between coal and its impurities. This method uses dry air, so it has the advantage of not requiring the coal to be dewatered. In this method, coal is subjected to an electrostatic charge and then fed into drums of opposite polarities. The nonconductive coal particle retains the charge and is attracted to the drum. A blade then scrapes the coal off the drum into a collector bin. The conductive sulfur and ash-bearing minerals are collected on a grounded drum. Leveled cleaning cost for a 500-MW power plant is claimed to be \$13.11/ton of clean coal. Table 11 lists the processing results using this technique.

Table 10

Dow Process Results (Integrated Plant)

| Coal/Property | Feed | Dow |
|------------------------------|-------|------|
| Upper Freeport Coal | | |
| Total sulfur, wt % | 2.5 | 1.1 |
| SO ₂ reduction, % | | 66.4 |
| Ash, wt % | 29.8 | 9.5 |
| Btu recovery, % | 100.0 | 89.4 |
| Lower Freeport Coal | | |
| Total sulfur, wt % | 4.3 | 1.4 |
| SO ₂ reduction, % | | 73.9 |
| Ash, wt % | 21.4 | 6.0 |
| Btu recovery, % | 100.0 | 87.2 |
| Pittsburgh No. 8 Coal | | |
| Total sulfur, wt % | 3.6 | 2.2 |
| SO ₂ reduction, % | | 66.4 |
| Ash, wt % | 29.8 | 9.5 |
| Btu recovery, % | 100.0 | 92.9 |

High-Gradient Magnetic Separation

High-gradient magnetic separation (HGMS) is based on the difference in magnetic properties between coal and mineral impurities. The process involves grinding coal to -200 mesh and forming a slurry with water. The slurry is then subjected to a high-intensity magnetic field in a container packed with stainless steel wool. The wool traps the magnetically charged pyrite and ash particles while allowing the nonmagnetic coal particles to pass through. HGMS has been claimed to recover 95 percent of the coal product while reducing 80 to 90 percent of the pyrite and 35 to 45 percent of the ash.³⁵

High-gradient magnetic separation has not been commercialized, mainly because of the high capital cost of conventional iron magnets and the method's inability to produce satisfactory yields when processing minus-28-mesh material.³⁶ If these problems could be overcome, operating costs for HGMS would be \$9.58/ton.³⁷

Agglomeration

Another method of processing fine coal is agglomeration. This technique relies on the surface properties of the coal and mineral matter. Coal fines are mixed with water

³⁵A. C. Wright.

³⁶A. C. Wright.

³⁷F. V. Karlson, et al., "The Potential of Magnetic Separation in Coal Cleaning," *Proceedings: Symposium on Coal Cleaning to Achieve Energy and Environmental Goals*, Vol I, S. E. Rogers and A. W. Lemmons, Jr. (Eds.), EPA 600/7-78-098a (USEPA, April 1979).

Table 11

AED* Electrostatic Separation Process Results (Integrated Plant)

| Coal/Property | Feed | AED* |
|------------------------------|-------|------|
| Upper Freeport Coal | | |
| Total sulfur, wt % | 2.5 | 1.5 |
| SO ₂ reduction, % | | 51.6 |
| Ash, wt % | 29.8 | 14.9 |
| Btu recovery, % | 100.0 | 90.0 |
| Lower Freeport Coal | | |
| Total sulfur, wt % | 4.3 | 1.9 |
| SO ₂ reduction, % | | 62.5 |
| Ash, wt % | 21.4 | 10.4 |
| Btu recovery, % | 100.0 | 89.0 |
| Pittsburgh No. 8 Coal | | |
| Total sulfur, wt % | 3.6 | 2.4 |
| SO ₂ reduction, % | | 39.7 |
| Ash, wt % | 29.8 | 7.9 |
| Btu recovery, % | 100.0 | 93.5 |

*Advanced Energy Dynamics.

to form a slurry of about 20 percent coal fines by weight. The solution is frothed and mixed with an agglomerating medium, usually an oil. The agglomerating medium selectively adheres to the coal particles but not to the mineral matter. The mixture of coal and agglomerant coalesce together and then are skimmed from the top of the mix.

Oil agglomeration can recover about 90 percent of the coal's Btu value while reducing ash by 75 percent and sulfur by 50 percent.³⁸ The main advantage of agglomeration over flotation is that it can treat extremely fine coal (below 44 μm) while maintaining recovery levels higher than 90 percent; in addition, it can process coal with poor washability.

National Research Council of Canada (NRCC) Oil Agglomeration Process

In this process, No. 2 fuel oil is used as the agglomerant by mixing it with a 10 percent solids coal/water slurry. A 3- to 5-ton/hr pilot plant is owned and operated by Scotia Liquicoal Limited as a sublicensee to NRCC. Processing performance results are listed in Table 12.

³⁸L. E. Burgess, et al.

Table 12

NRCC Oil Agglomeration Process Results (Integrated Plant)

| Coal/Property | Feed | NRCC |
|------------------------------|------|------|
| Upper Freeport Coal | | |
| Total sulfur, wt % | 2.5 | 1.5 |
| SO ₂ reduction, % | | 52.0 |
| Ash, wt % | 29.8 | 11.3 |
| Btu recovery, % | 100 | 90.3 |
| Lower Freeport Coal | | |
| Total sulfur, wt % | 4.3 | 2.0 |
| SO ₂ reduction, % | | 61.1 |
| Ash, wt % | 21.4 | 7.6 |
| Btu recovery, % | 100 | 90.1 |
| Pittsburgh No. 8 Coal | | |
| Total sulfur, wt % | 3.6 | 2.6 |
| SO ₂ reduction, % | | 33.8 |
| Ash, wt % | 29.8 | 6.8 |
| Btu recovery, % | 100 | 91.7 |

Otisca T-Process

Otisca Industries, Ltd., is promoting a coal-cleaning process for "ultraclean coal" called the Otisca T-Process.³⁹ It is claimed to consistently produce a clean coal with an ash content of under 2 percent while rejecting virtually all of the pyritic sulfur and obtaining higher than 95 percent Btu recovery. The Otisca T-Process is similar to oil agglomeration processes in that it is based on separation by two immiscible streams; however, a hydrocarbon is used as the agglomerant. The cleaned coal can either be dried for use in a pulverized-coal burner, briquetted, or made into a coal-water slurry.

A 2-ton/hr pilot plant has been in operation since 1983 and is proving effective. The pilot facility has produced 34,000 gal of coal-water slurry. A larger 15-ton/hr plant has been built and is capable of producing coal-water slurry for \$4.30/MBtu. This figure is the delivered price to consumers' tanks within a 70-mile radius of the plant. The plant is also equipped to produce large quantities of low-ash, engine-grade fuel for diesel and

³⁹D. Keller and F. Simmons, "Two Ton-Per-Day Production of Otisca T-Process Ultra-Clean Coal/Water Slurry," paper presented at the Tenth International Coal Preparation Congress, Edmonton, Canada (September 1986); D. V. Keller, "Coal Refining by Physical Methods for the Preparation of Coal Slurries With Less Than One Weight Percent Ash," paper presented at the Fifth International Symposium on Coal Slurry Combustion and Technology, Tampa, FL (April 1983).

turbine testing. Exclusive use of the process for coal cleaning could result in operating costs of \$5.54/ton.⁴⁰

Otisca surveyed some 100 seams of coal and found that more than half can yield a product coal with ash contents in the range of 1 weight percent; several raw coals can be reduced to below 0.3 weight percent ash and a few to under 0.1 weight percent ash. In all cases, product coal Btu yields are higher than 95 percent and most often greater than 98 percent. Table 13 summarizes performance of a typical raw coal-cleaning run.

The Otisca T-Process shows promise as a coal-cleaning method. Although it is limited to pyritic sulfur removal, organic sulfur could be removed by combining the process with a chemical method. The process has proven effective in a 2-ton/day plant and plans are underway for a 15-ton/day plant, as mentioned above.

The Otisca T-Process cannot be done onsite. Otisca Industries sells its product fuel but the process itself cannot be copied because the hydrocarbon agglomerant is proprietary.

Table 13
Typical Otisca T-Process Cleaning Results

| Property | Raw Feed | Product | |
|------------------------|----------|---------|----------------|
| | | Coal | Mineral Matter |
| Ash (wt %) | 6.98 | 0.57 | 84.13 |
| Volatile matter (wt %) | 35.46 | 35.30 | 13.45 |
| Fixed carbon (wt %) | 57.56 | 64.14 | 2.42 |
| Total sulfur (wt %) | 0.78 | 0.68 | 1.47 |
| Heating value (Btu/lb) | 13,898 | 14,473 | 1,007 |
| Yield (wt %) | - | 92.6 | 7.4 |

⁴⁰C. D. Smith, "Coal Cleaning by the Otisca Process," *Proceedings: Symposium on Coal Cleaning to Achieve Energy and Environmental Goals*, Vol I, S. E. Rogers and A. W. Lemmons, Jr. (Eds.), EPA-600/7-78-098a (USEPA, April 1979).

7 CONCLUSIONS AND RECOMMENDATIONS

USACERL has surveyed the state of the art in microcleaning technology to determine its applicability to Army coal-fired plants. Three advanced types of microcleaning have been investigated: chemical, biological, and physical. These processes were analyzed with respect to specifications the Army has established (see Chapter 1).

For background information, the coal-cleaning concept was reviewed and pertinent legislation summarized. Microcleaning technology was then explained.

Two chemical processes were evaluated: alkali leaching and microwave irradiation. Although these methods have been commercialized and are being used at some plants, they are still relatively new and untested. Several other chemical removal processes are still under development. Chemical extraction could be very desirable once perfected because it is probably the only treatment that will remove organic sulfur.

Biological processes involve the use of microorganisms to metabolize the sulfur into water-soluble forms. These processes are very new and are still the subject of debate among scientists studying them. At present, the most promising use of microbes is in biosurface modification to enhance flotation (a physical removal process).

The physical processes investigated include advanced flotation, true liquid beneficiation, electrostatic separation, high-gradient magnetic separation, and agglomeration. Some physical cleaning methods have been in use for many years. The primary drawback is that these processes remove only inorganic sulfur; organic forms of sulfur must also be eliminated to achieve the SO_x standards. Some of the advanced physical methods show promise once they have been refined; when used in combination with effective chemical processes, both forms of sulfur could possibly be removed.

Coal cleaning prior to combustion is an important option to consider in attempting to reduce SO_x emissions at the lowest possible cost. Depending on the amount of pyritic sulfur in the feedstock coal, conventional cleaning methods can effectively remove 20 to 60 percent of the total sulfur at very low processing costs. At least one organization (TVA) is using a successful combination of FGD and precombustion coal cleaning, with savings of up to 22.6 percent documented for SO_x control. The positive results of these combined processes have led TVA to develop a computer model to optimize the cost/ SO_x removal based on coal quality and boiler operating conditions.

Most of the advanced cleaning technologies described in this report are not yet commercially available. In terms of potential, the chemical and biological methods could be capable of removing more than 90 percent of all forms of sulfur, while advanced physical methods could remove between 80 and 99 percent of pyritic sulfur. Depending on the feedstock quality, these advanced techniques are potentially cost-competitive with conventional FGD technologies. Table 14 compares typical FGD costs with those estimated for the advanced microcleaning methods described in this report.

Since the advanced processes have not been fully field-tested, the economics of various coal-cleaning plant sizes have not been defined. With the exception of the biological methods, advanced microcleaning plants in the 1- to 10-ton/hr (24- to 240-ton/day) size would probably not be economical. However, preliminary studies conducted

Table 14

**Coal Microcleaning vs. Flue Gas Desulfurization:
Cost Comparison**

| Process | Cost/Ton (1988 Dollars) |
|-----------------------------------|----------------------------|
| Microcleaning | |
| Chemical Methods | |
| TRW Gravimelt Process | 29.33 |
| GE Microwave Process | 35.30 |
| Biological Methods | 23.21 - 27.02 |
| Physical Methods | |
| Advanced flotation (DOE process) | 9.81 |
| ISGS aggregate flotation | 36.29 |
| True liquid beneficiation (DOW) | 13.24 |
| Electrostatic separation (AED) | 13.11 |
| High-gradient magnetic separation | 9.58 |
| Agglomeration (Otisca T-Process) | 5.54 |
| Flue Gas Desulfurization* | |
| Wet processes | 28.84 - 33.85 |
| Dry processes | 18.81 |

*Data are from A. E. Martin (Ed.), *Emission Control Technology for Industrial Boilers* (Noyes Data Corp., 1981).

by DOE's Oak Ridge National Laboratory indicate that a centralized 1500-ton/day (62.5-ton/hr) plant built to serve several boiler plants could be cost-effective.⁴¹

Based on these findings, the following recommendations were developed:

1. Advanced microcleaning at Army coal-fired boilers should not be considered at this time. The processes capable of reducing sulfur and ash to 1 and 6 percent, respectively, are not yet commercially available.

2. If coal-water slurry technology is being considered for a facility, microcleaning should be investigated since it would eliminate the need (and cost) to dewater the coal after cleaning.

⁴¹S. P. N. Singh and G. R. Peterson, *Survey and Evaluation of Current and Potential Coal Beneficiation Processes*, ORNL/TM-5953 (DOE, March 1979).

3. The Army should keep up to date on SO_x control technologies used by utility-scale boilers and on the developing microcleaning processes. Now that stricter acid-rain legislation has been passed, it is becoming increasingly important to determine the most cost-effective method of reducing SO_x emissions.

4. Because of the success TVA has made in combining FGD with conventional coal-cleaning processes, further research should be conducted to determine where this approach could be used instead of using low-sulfur coal.

METRIC CONVERSION FACTORS

| | | |
|------------|----|--------------------------|
| 1 in. | = | 25.4 mm |
| 1 ft | = | 0.305 m |
| 1 mi | = | 1.61 km |
| 1 lb | = | 0.453 kg |
| 1 lb/cu ft | = | 16.178 kg/m ³ |
| 1 oz | = | 28.35 g |
| 1 gal | = | 3.78 l |
| 1 sq in | = | 645.2 mm ² |
| 1 sq ft | = | 0.093 m ² |
| 1 acre | = | 0.405 hectare |
| 1 cu ft | = | 0.028m ³ |
| 1 psi | = | 6.89 kPa |
| | °C | = 0.55(°F-32) |

REFERENCES

- Andrews, G. F., and J. Maczuga, "Bacterial Removal of Pyrite From Coal," *Fuel*, Vol 63 (March 1984).
- Attia, Y. A., *Processing and Utilization of High Sulfur Coals* (Elsevier, 1985).
- Attia, Y. A., and M. A. Elezky, "Biosurface Modification in the Separation of Pyrite From Coal by Froth Flotation," paper presented at the First International Conference on Processing and Utilization of High Sulfur Coals, Ohio State University (October 1985).
- Baur, P. S., "Coal Cleaning to Improve Boiler Performance and Reduce SO₂ Emissions," *Power*, Vol 125, No. 9 (September 1981).
- Boron, D., and R. Kollack, "Prospects for Chemical Coal Cleaning," *Mining Engineering*, Vol 8, No. 2 (February 1986).
- Burger, J., "Three New Approaches to the Problem of Dewatering Fine Coal," *Coal Age*, Vol 21, No. 1 (January 1986).
- Burgess, L. E., et al., "The AFT Beneficiation System: A New Way to Clean Coal," paper presented at the Fifth International Symposium on Coal Slurry Combustion and Technology, Tampa, FL (April 1983).
- "Economic Indicators," *Chemical Engineering*, Vol 95, No. 6 (April 15, 1988), p 9.
- Federal Register*, Vol 52, No. 241 (16 December 1987), 40 CFR Part 60.
- Given, P. H., *Fuel*, Vol 39, No. 147 (1960).
- Hall, E. H., and G. E. Raines, "The Use of Coal Cleaning for Complying With SO₂ Emission Regulations," *Proceedings: Symposium on Coal Cleaning to Achieve Energy and Environmental Goals*, Vol I, S. E. Rogers and A. W. Lemmons, Jr. (Eds.), EPA 600/7-78-098a (USEPA, April 1979).
- Horazak, D. A., et al., *Gas Turbine Systems Research and Development Program* (U.S. Department of Energy, February 1986).
- Karlson, F. V., et al., "The Potential of Magnetic Separation in Coal Cleaning," *Proceedings: Symposium on Coal Cleaning to Achieve Energy and Environmental Goals*, Vol I, S. E. Rogers and A. W. Lemmons, Jr. (Eds.), EPA 600-7-78-098a (USEPA, April 1979).
- Keller, D. V., "Coal Refining by Physical Methods for the Preparation of Coal Slurries With Less Than One Weight Percent Ash," paper presented at the Fifth International Symposium on Coal Slurry Combustion and Technology, Tampa, FL (April 1983).
- Keller, D., and F. Simmons, "Two Ton-Per-Day Production of Otisca T-Process Ultra-Clean Coal/Water Slurry," paper presented at the Tenth International Coal Preparation Congress, Edmonton, Canada (September 1986).

USACERL DISTRIBUTION

Chief of Engineers

ATTN: CEIM-SL (2)

ATTN: CERD-L

USAEHSC

ATTN: Library 22060

ATTN: CEHSC-FU

US Army Engineer Districts

ATTN: Library (42)

US Army Engineer Divisions

ATTN: Library (13)

US Army Europe

ODCS/Engr 09403

USA AMCCOM 61299

ATTN: AMSMC-RI

ATTN: AMSMC-IS

FORSCOM

ATTN: DEH (28)

HSC

Ft. Sam Houston AMC 78234

ATTN: HSLO-F

Fitzsimons AMC 80045

ATTN: HSHG-DEH

Walter Reed AMC 20307

ATTN: Facilities Engineer

Tyndall AFB, FL 32403

AFESC/Engineering & Service Lab

Naval Facilities Engineering Command

ATTN: Code 1652B 22332

NCEL 93043

ATTN: Library (Code L08A)

Defense Technical Info. Center 22314

ATTN: DDA (2)

Natl Guard Bureau 20310

Installation Division

US Army Env. Hygiene Agency

ATTN: HSHB-E 21010

National Bureau of Standards 20899

NEESA

ATTN: Code 111C 93043

GMPA

ATTN: STRGP-FT 17070

DFSC

ATTN: DFSC-PR 22314

115

2/89

TRADOC

HQ, TRADOC, ATTN: ATEN-DEH 23651

WESTCOM

Fort Shafter 96858

ATTN: DEH

ATTN: APEN-A

FORT BELVOIR, VA 22060

ATTN: Canadian Liaison Officer

ATTN: British Liaison Officer

ATTN: Australian Liaison Officer

ATTN: French Liaison Officer

ATTN: German Liaison Officer

CECRL, ATTN: Library 03755

WES, ATTN: Library 39180

- Kilgroe, J. D., et al., *Coal Cleaning Options for SO₂ Emission Reduction*, EPA/600/D-85/057 (USEPA, March 1985).
- Killmeyer, R. P., "Selective Agglomeration: Let's Compare the Emerging Processes," *Coal Mining* (September 1985), pp 45-49.
- Koury, D. L. (Ed.), *Coal Cleaning Technology* (Noyes Data Corp., 1981).
- Merritt, P. C., "Advanced Coal Cleaning Processes Sought for Superclean Coal," *Coal Age* (June, 1986).
- Meyers, R. A., *Coal Desulfurization* (Marcel Dekker, 1977).
- Meyers, R. A., "Gravimelt Process Applications and Economics," Proceedings of the First Annual Pittsburg Coal Conference (DOE, September 1984).
- Miller, K. J., "Fine Grinding and Flotation to Desulfurize Coal," paper presented at the First International Conference on Processing and Utilization of High Sulfur Coals, Ohio State University (October 1985).
- Murphy, J., et al., "Coal Desulfurization by Microbial Processing," paper presented at the First International Conference on Processing and Utilization of High Sulfur Coals, Ohio State University (October 1985).
- Phillips, P. J., and R. M. Cole, "Economic Penalties Attributable to Ash Content of Steam Coals," paper presented at the AIME Annual Meeting, New Orleans (February 1979).
- Rissatti, J. B., and K. W. Miller, "Rates of Microbial Removal of Organic and Inorganic Sulfur from Illinois Coals and Coal Chars," paper presented at the Illinois Coal Development Board Fourth Annual Contractors' Meeting, Urbana, IL (September 1986).
- Singh, S. P. N., and G. R. Peterson, *Survey and Evaluation of Current and Potential Coal Beneficiation Processes*, ORNL/TM-5953 (DOE, March 1979).
- Smith, C. D., "Coal Cleaning by the Otisca Process," *Proceedings: Symposium on Coal Cleaning to Achieve Energy and Environmental Goals*, Vol I, S. E. Rogers and A. W. Lemmons, Jr. (Eds.), EPA 600-7-78-098a (USEPA, April 1979).
- Spaite, P. W., et al., *Environmental Assessment of Coal Cleaning Processes: Technology Overview*, EPA-600/7-79-073, (USEPA, September 1979).
- Tarkington, T. W., F. M. Kennedy, and J. G. Patterson, *Evaluation of Physical/Chemical Coal Cleaning and Flue Gas Desulfurization*, EPA-600/7-79-250 (USEPA, November 1979).
- Use of Coal Cleaning in Bubbles Trade-Offs and Acid Rain Legislation*, Proceedings: First Annual Pittsburgh Coal Conference (September 1984), p 374.
- Wright, A. C., "Collecting Fines for New Markets," *Coal Age*, Vol 90, No. 1 (January 1985).
- Wright, C. R., L. Larkin, F. M. Kennedy, and T. W. Tarkington, *Computer Economics of Physical Coal Cleaning and Flue Gas Desulfurization*, EPA-600/7-85-039 (USEPA, September 1985).