



Project Summary

Assessment of Coal Cleaning Technology: Final Report

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Tests at seven coal preparation plants evaluated the performance of froth flotation cells and dense-medium cyclones in removing ash and sulfur (S) from fine coal (minus 28 mesh). Flotation circuits tested at four plants showed substantial reductions in coal ash content (64-88%), pyritic S content (48-65%), and sulfur dioxide (SO₂) emission (expressed as ng SO₂/J or lb SO₂/10⁶ Btu; 15-87%) at mean weight recoveries of 11-54%. Dense-medium cyclones tested at three plants showed reductions in coal ash content (43-75%), pyritic S content (29-67%), and SO₂ emission (16-40%) at mean weight recoveries of 63-83%. Data from other coal preparation plants demonstrated that physical coal cleaning (PCC) reduces the variability as well as the mean value of the coal ash and S contents. Raw and clean coal data sets were found to exhibit statistical properties which can be characterized by time series models. The use of low S coal, PCC, or chemical coal cleaning (CCC) was evaluated for compliance with potential SO₂ emission limits for industrial boilers. PCC can achieve moderate S reductions in (high S) Northern Appalachian and Midwestern coals, but few of these coals can be cleaned to meet a 516 ng SO₂/10⁶ Btu standard. Many Southern Appalachian, Alabama, or Western coals are capable of meeting this standard as mined or after cleaning. Many CCC processes can be used to desulfurize high S coals for compliance with this standard. Eleven major CCC processes were evaluated for their performance potential. Some processes can remove as much as 90-95% of the pyritic S and up to 40% of the organic S from raw coal.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Although approximately 60% of underground coal and 20% of surface mined coal is cleaned in some way, physical coal cleaning (PCC) has not been fully exploited. Chemical coal cleaning (CCC) has not been used commercially. Many facets of these technologies were explored under EPA's sponsorship, and this Coal Cleaning Technology Assessment project was part of that effort. This project included:

- A comprehensive evaluation of existing performance data and costs of PCC equipment with respect to S removal.
- Development of new data necessary to complete the evaluation of the performance of coal cleaning equipment and processes.
- An evaluation of fine coal dewatering and handling technology, including costs.
- An evaluation of coal preparation requirements for synthetic fuel conversion processes.
- An engineering and economic evaluation of CCC processes.
- An assessment of coal cleaning as a pollution control technology for industrial boilers.
- An evaluation of the reduction in S variability of coal by commercially operating coal cleaning plants.

The report is based on information gathered, data generated, and engineering analyses performed by Versar during the period 1978 through 1980.

Equipment Performance Studies

Domestic and foreign equipment manufacturers were contacted and their equipment data were compiled and evaluated as part of this effort. Also, actual in-plant performance of froth flotation cells and dense-medium cyclones was evaluated for S and ash removal. A mobile laboratory was outfitted and deployed to support the sampling and analytical work at seven coal preparation plants. The equipment types, plant locations, and coal sources tested are shown in Table 1.

As shown in Table 1, flotation circuits at four selected coal preparation plants were sampled. In addition, samples of the plant raw coal feed, product coal, and refuse were characterized in an effort to gain information on the overall performance of the plants. Each plant contains one flotation circuit except plant 1-D, which has a fine coal and a coarse coal flotation circuit; however, only the coarse coal flotation circuit was evaluated. In all but one plant, five sets of coal samples were collected (each set on a different day) to determine the variability of the measured parameters (e.g., pyritic S content) with time.

Ash, pyritic S content, and SO₂ emission (ng SO₂/J or lb SO₂/10⁶ Btu) of the product streams for all circuits were found to be lower than those for the corresponding feed streams at mean weight recoveries of 11–54%. Mean ash recoveries for all tested circuits were 64–88%. The range for pyritic S reduction was 48–65%. Mean reduction in SO₂ emission was 15–87%.

All of the tested flotation circuits, except the one in plant 1-C, show that the flotation products contain less weight percent S than the feed. The result for plant 1-C was verified by repeating the total S tests at Versar's analytical laboratory: the same conclusion was reached from the analysis of these test results. The increase in total S concentration can be explained by the constant organic S concentration in the pure coal portion (as opposed to ash) of the feed and product streams. Based on the laboratory analyses, the organic S content in the feed coal is about 30% of the total S. As most of the ash in the feed coal is removed by the flotation process, the pure coal content, and therefore the

Table 1. Coal Types and Circuits Sampled for Equipment Performance Testing

Plant	Circuit Tested	Plant Location	Coal Type
1-A	Froth flotation	Franklin County, IL	Illinois No. 6, Franklin County
1-B	Froth flotation	Indiana County, PA	Upper Freeport Coal, Indiana County
1-C	Froth flotation	Raleigh County, WV	Peerless Seam, Raleigh County
1-D	Froth flotation (Shakedown tests)	Colfax County, NM	Colfax County
2-A	Dense-medium cyclone	Raleigh County, WV	Pocahontas No. 3 Seam
2-B	Dense-medium cyclone	Wyoming County, WV	Williamson Seam No. 2
2-C	Dense-medium cyclone	Wise County, VA	Blend of Norton, Dorchester, Lyons, Clintwood, and Elkhorn Rider Seams

weight concentration of S, in the product stream increases.

Figure 1 shows the reduction in percent SO₂ emission as a function of percent weight recovery from the froth flotation circuit for each plant tested. For plants 1-A (Bank 1 and 2) and 1-C, the reduction in SO₂ emission increases for lower percent weight recoveries. For plant 1-B, the data are scattered.

Three coal preparation plants (plants 2-A, 2-B, and 2-C) shown in Table 1 were selected for testing of dense-medium cyclones. Each of the three plants uses 61 cm (24 in.) diameter dense-medium cyclones as the only coal cleaning device in the process. Feed size of the coal to the cyclones is 38.1 mm × 0 (1-1/2 in. × 0) for plants 2-A and 2-C, and 9.4 mm × 0 (3/8 in. × 0) for plant 2-B.

Feed, product, and refuse streams associated with the dense-medium cyclones were sampled for 5 consecutive days, and analyzed for ash, pyritic and total S, and heating value. The test results show that cleaning of coal in dense-medium cyclones resulted in a product containing less ash, less total and pyritic S, and higher heating value. SO₂ emission decreased as a result of this cleaning process. Mean reductions from the three dense-medium cyclone circuits were 43–75% for ash, 39–67% for pyritic S, 2–18% for total S, and 16–40% for SO₂ emission at mean recoveries of 63–83%.

The primary interest of this study is the performance of a dense-medium cyclone in reducing SO₂ emission. Data from 5-day samples were used to plot the weight recovery of the cleaned coal as a function of SO₂ emission reduction (Figure 2). The results show that the quality of the product, in terms of SO₂

emission, becomes poorer as more material is recovered from the dense-medium cyclones.

Fine Coal Dewatering

An engineering study evaluated some alternatives for fine coal dewatering and drying. Costs to a preparation plant operator for alternative dewatering and drying schemes were compared to the economic benefits achieved by shipping drier coal to a 580 MW electric utility. A base case with no dewatering was also included in the study.

Seven alternative schemes for coal dewatering and drying were evaluated in this study:

- Case O – Base case using no dewatering.
- Case A – 9.5 × 0.6 mm fraction centrifuged and 0.6 mm × 0 fraction filtered.
- Case B – Same as A, but the 0.6 mm × 0 filter cake is dried with a heat exchanger.
- Case C – Same as A, but the 0.6 mm × 0 filter cake is dried in a direct heat thermal dryer.
- Case D – 9.5 × 0.6 mm centrate is processed in a hydro-cyclone for slimes removal.
- Case E – Same as D but slimes are removed by flotation cells.
- Case F – 9.5 × 0.6 mm is not centrifuged, but combined with 0.6 mm × 0 filter cake from vacuum filter and dried in direct heat thermal dryer.

The coal user (e.g., an electric utility) was assumed to contract for net heating value. For the purpose of analyzing dewatering and drying operations only,

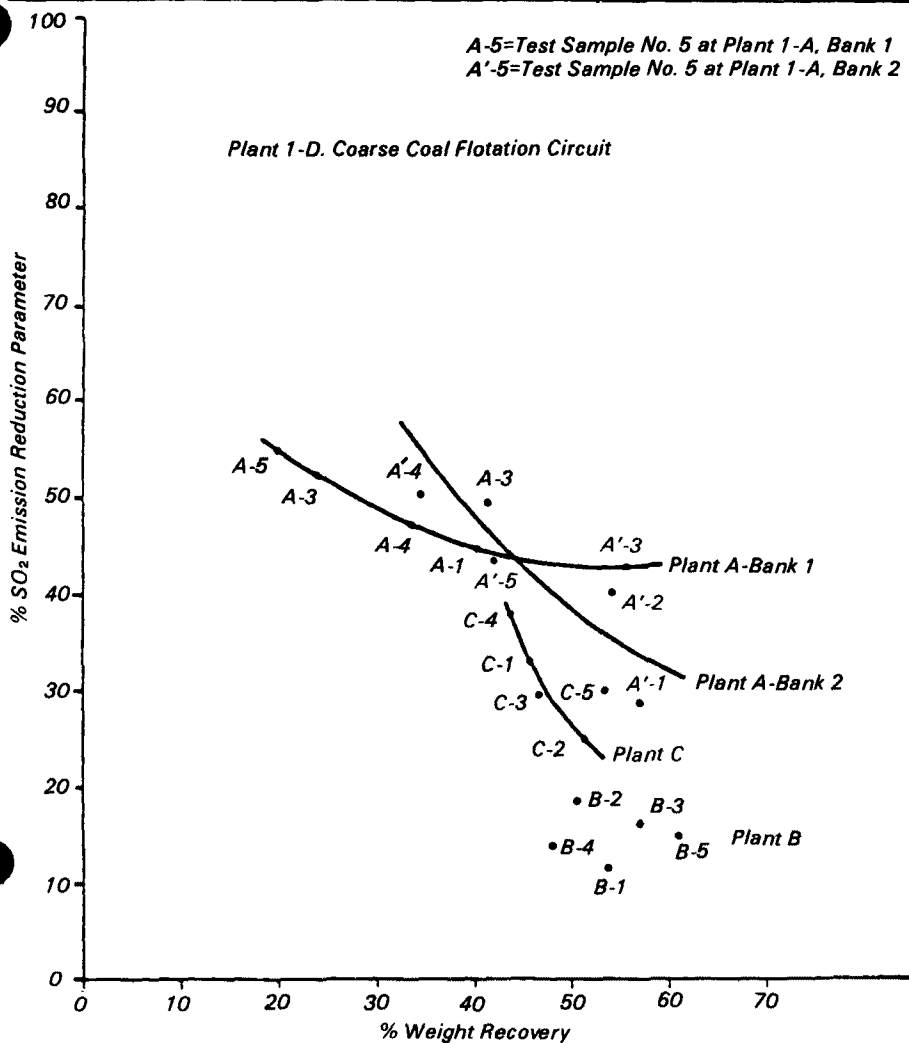


Figure 1. Plot of percent of SO₂ emission reduction vs. percent weight recovery for the flotation units tested at four plants.

constant heating value (31,751 J/g or 13,650 Btu/lb) of dry coal was assumed, since no appreciable change in coal composition results from these operations. However, any associated moisture in the coal received was penalized, for the purpose of this study, by the requirement for sufficient additional coal to vaporize this moisture. This additional coal penalty is the total cost of such coal through mining and the entire cleaning plant beneficiation process including separation, dewatering and drying, and refuse disposal; and was assumed to be \$22/Mg (\$20/ton) on a dry basis. In addition, a power plant pulverization cost of 60 cents per wet ton was assessed to the additional coal requirement.

Table 2 shows that the fine coal dewatering and drying alternatives have significant benefits compared to the

baseline case of no dewatering. It is instructive to compare the net benefits to those of Case A \$3.41/Mg (\$3.10/ton), which is limited to mechanical dewatering processes. Case B, in which the filter cake is dried in an indirect heat exchanger, is only marginally more attractive. Case C, where a direct thermal dryer is used, is significantly less attractive than Case A. In Cases D and E, the recovery of solids from the centrate appears attractive, reflecting lower refuse disposal costs as well as recovered product values. The use of a thermal dryer in Case F to avoid centrate solids losses is apparently competitive with Cases D and E.

Pollution From Coal Cleaning Processes

Coal cleaning can significantly reduce SO₂ emissions, scrubber sludge from

air pollution control equipment, and ash from coal-fired boilers. However, the coal cleaning process itself generates emissions to air, water, and land.

Samples obtained from 11 coal preparation plants and auxiliary areas (e.g., refuse piles) were analyzed for the 65 classes of pollutants identified under the court-approved Consent Decree of July 7, 1976. Among the non-organic priority pollutants detected in untreated coal preparation plant wastewaters were Sb, As, asbestos, Be, Cd, Cr, Cu, cyanide (CN), Pb, Hg, Ni, Ag, Se, Tl, and Zn compounds. Settling appeared to be effective in removing all these elements except Cd, Pb, Hg, Ag, Se, and Tl. In general, analytical data showed significant amounts of dissolved metallic elements in the process waters. This result agrees with the fact that the coal processing medium remains slightly alkaline. Such a medium is not likely to dissolve metallic minerals present in the coal. Some organic compounds were detected, but these were found to be the results of laboratory contamination or processes other than the mining or cleaning of coal. Suspended solids were found to be the principal pollutant in coal preparation plant wastewaters.

Analysis of data for leachate and runoff from coal storage, refuse piles, and coal preparation plant ancillary areas showed that waste loadings and resulting effluent qualities were very similar and appeared to be independent of the processing methods that were used in the respective plants. The principal pollution control measure associated with coarse waste disposal is compaction and coverage with soil to minimize the chances for oxidation and percolation. This also reduces the possibility of fire, another major environmental problem with refuse piles.

Sulfur Reduction and Variability

The ability of boiler operators to comply with emission regulations and the costs associated with such compliance also depend on the variabilities of coal S content and heating value. When the emission regulation is expressed in terms of maximum SO₂ emission in ng SO₂/J (lb SO₂/10⁶ Btu), the mean SO₂ emission of a coal burned in boilers must be lower than this maximum value. The reason for using a coal with a lower SO₂ emission is to prevent non-compliance (exceedance) during positive excursions around the mean. Two factors determine how much lower the

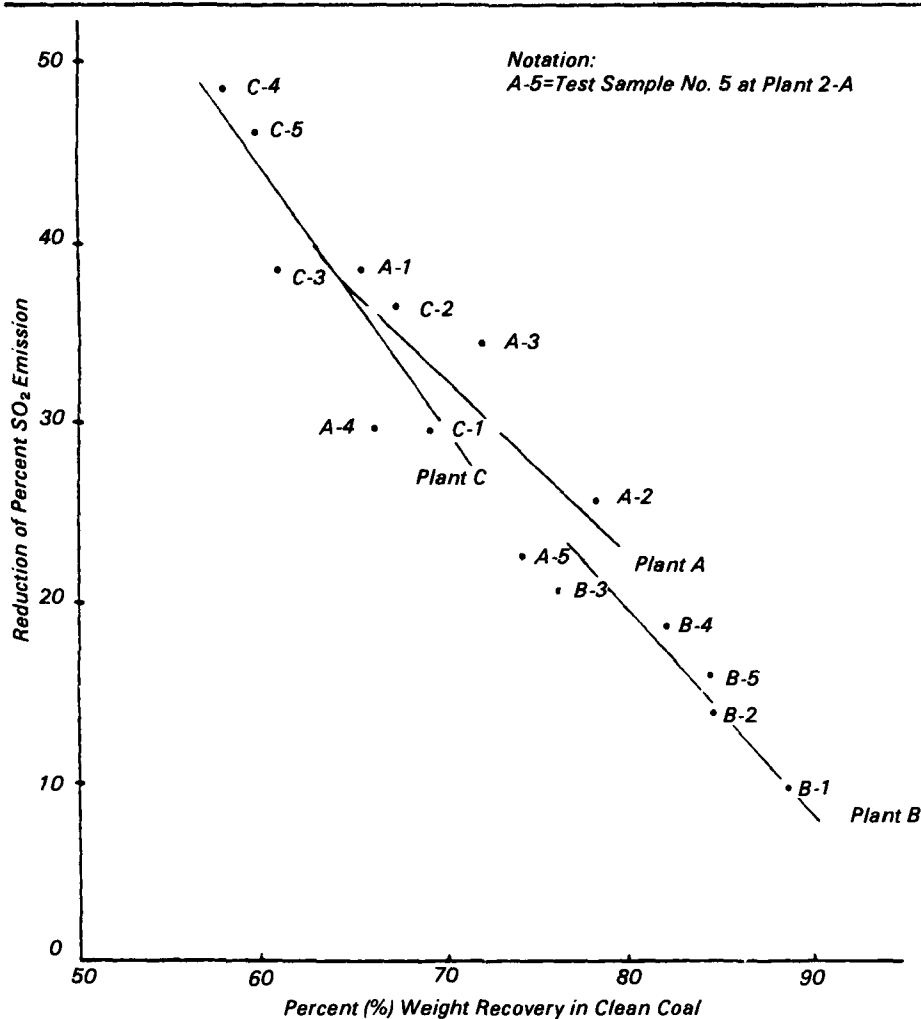


Figure 2. Plots of percent weight recovery vs. percent reduction of SO₂ emission for the dense-medium cyclones tested at three coal preparation plants.

Table 2. Costs and Benefits Per Dry Ton of Fine Coal Product^{a,b}

Case	Fine Coal Dewatering and Drying Operations	Cost, \$/Mg	Benefit, \$/Mg	Net Benefit, \$/Mg
0	None	0.00	0.00	0.00
A	Centrifugation, Filtration	1.02	4.43	3.41
B	Centrifugation, Filtration, Indirect Heat Exchange	1.35	4.79	3.44
C	Centrifugation, Filtration, Direct Thermal Dryer	2.16	4.91	2.75
D	Centrifugation, Filtration, Hydrocyclone, Filtration	0.97	4.69	3.72
E	Centrifugation, Filtration, Flotation, Filtration	0.88	4.87	3.99
F	Filtration, Direct Thermal Dryer	1.85	5.57	3.72

^a1977 dollars.

^bOperations listed were performed on partial streams.

mean SO₂ emission must be than the emission limit: (1) the fractional time that the regulations permit a boiler to exceed the nominal limit (confidence level), and (2) the characteristic variability in the coal feed (mean value, standard deviation, and autocorrelation structure). Quantification of the second factor (i.e., the characteristic variability of heat-specific S content in coal) was a prime objective of two studies: (1) one that discusses the effect of PCC on the S content and S variability in coal, and (2) an evaluation of the effect of PCC on attenuating coal S variability.

Effect of PCC on the Content and Variability of Sulfur

Using existing PCC plant data as a basis, the first study sought to achieve two primary objectives: (1) documentation of the performance of commercial coal cleaning facilities in removing S from coal, and (2) quantification of variability of the coal's SO₂ emission.

The database used in this study consists of 53 data sets, with a total of 3,204 data points. Each data set represents an identifiable and unique coal stream, either raw coal or cleaned coal, from a particular cleaning plant or loading facility, with the source of the coal (seam and county) and cleaning level specified. Eight coal preparation plants provided data sets for both feed and product coal; and approximately 40 others submitted only single values for feed and product measurements. The remaining plants provided product data without the corresponding feed values.

The analysis from the matched pairs of data sets for S, Btu, and SO₂ emission supported the following conclusions:

- In each of the eight plants for which matched pairs of feed and product data were available, both the absolute standard deviation and the relative standard deviation (RSD) for all three coal characteristics were reduced by the coal preparator process.
- The raw and clean coal RSDs vary from plant to plant, and no typical values are universally valid.

This study revealed a need for further investigation of coal S variability for several reasons. One of the reasons was that the effect of cleaning on S variability could not be well quantified from this study because of the insufficient paired data for raw and cleaned coal. Also, correlation of S content in coal sample could not be quantified reliably because sampling and analysis procedures used

by the various coal companies who provided the data were not uniform.

Effect of PCC on Attenuating Coal Sulfur Variability

The second study was conducted as a controlled experimental investigation to accurately collect and analyze representative samples of raw and clean coal. Raw and clean coal samples were collected from two coal preparation plants so that hour-to-hour and day-to-day changes in the coal characteristics could be monitored. These samples were collected and analyzed consistently during the study period using standard techniques so that the variance associated with sampling and analysis would not mask changes in the coal characteristics.

Sampling both feed and product coals from each of two coal preparation plants, under carefully controlled conditions, confirmed the results of prior studies. Both the mean total S content and the mean SO₂ emission are significantly reduced by the cleaning process as shown in Table 3.

The extent of the reduction is quite different for the two plants. In fact, the 63.4% SO₂ emission reduction at Plant No. 2 is uncharacteristically high for many existing coal preparation plants. However, a wide range of reductions among preparation plants is a result consistent with prior findings.

Prior to analyzing the variability in coal data, the measurement uncertainty in the data was independently determined. This uncertainty, attributable to the process of sampling, compositing, sample preparation, and laboratory analysis, provides a quantitative limitation to subsequent explanations of coal variability. All values for aggregate measurement uncertainty were significantly less than the total variations. Real variability in coal characteristics therefore was observed, over and above the measurement noise level.

For much of the data acquired in this study, strong autocorrelation was indicated. The 30-minute increment data from Plant No. 1 were more highly autocorrelated than composite data over longer time intervals. The data from the Plant No. 2 exhibited weaker autocorrelation than the Plant No. 1 data. However, the results from both plants confirm that serial correlation of coal data does exist over short time intervals.

Two analytical techniques were utilized to quantify the correlated and ran-

Table 3. Effect of PCC on Coal Sulfur

Parameter		Plant No. 1	Plant No. 2
		30-Min Increments	1-Hour Increments
Total S, %	Raw Coal	3.076	2.576
	Cleaned Coal	2.612	1.309
	Reduction	15.1%	49.2%
lb SO ₂ 10 ⁶ Btu	Raw Coal	5.476	5.117
	Cleaned Coal	4.237	1.875
	Reduction	22.6%	63.4%

dom components of the variability in coal data: geostatistics and time-series analysis. Time-series analysis proved to be the more useful.

Time-series models can be used in a predictive way, to generate data sets much longer than the empirical (measured) data set. The random component in the predictive model is obtained from a random number generator. Since this model is probabilistic, many different time series, equally likely, may be generated, all based on the same mean, same variance, and same correlation structure. From a large number of time series based on the model for any single data set, the average expected number of emission violations by a power plant burning this coal (either raw or cleaned) can be estimated.

The time-series predictive model was also used to develop the effect of lot size on variability. The data generated by the time series were mathematically composited into successively longer time intervals (corresponding to successively larger quantities of coal in each interval). The sample mean variance decreases with increasing lot size, but at a smaller rate than would be expected from serially independent data. This relationship was more pronounced for clean coal than ROM coal at Plant No. 1.

Results of the second study showed that serial dependence (also called autocorrelation) of coal characteristics must be incorporated into any analysis of the ability of coal to comply with SO₂ emission regulations. The misapplication of Gaussian statistics, which assumes serial independence of coal data, leads to a gross underestimation of the frequency of short-term emission violations. Time series analysis, which combines serial dependence with a stochastic component to construct a predictive model, provides an alternative to Gaussian statistics. The tech-

niques and computer programs for applying time-series analysis are generally available for use.

Although the two diverse coals studied in detail both exhibited autocorrelation the magnitude of the autocorrelation component of the total variance differed from one coal to another and from raw to cleaned coal. Therefore, each coal's ability to meet short-term emission regulations must be determined separately until the number of different coals characterized is sufficient to generalize the variability of coal characteristics.

Evaluation of PCC as a Sulfur Control Technology for Industrial Boilers

A study was performed to support the EPA Office of Air Quality Planning and Standards in developing New Source Performance Standards (NSPS) for industrial boilers. The results were compiled in one of eight technology assessment reports for industrial boiler applications. This study was performed to determine the Best System of Emission Reduction (BSER) for industrial boilers. BSERs were defined as control technologies that could comply with a specified emission control level at minimum cost, energy, and environmental impact. The major pollutant considered for control was SO₂, although particulates, nitrogen oxides (NO_x), and other pollutants were included in relation to energy and environmental impacts of the chosen technologies.

Major decision variables considered in this study included the coal type and S control options, boiler types, and SO₂ emission control levels.

The sulfur control options are:

- Use of naturally occurring low S coal: considered to be coal with a S content of approximately 1% or less.

- Beneficiation of raw coal by PCC to remove ash and pyritic S.
- Beneficiation of raw coal by CCC to remove pyritic and/or organic S.

Multiple options were available within each type of control, and some preliminary evaluation and screening was required before detailed evaluations were performed.

The following items were considered in relation to the selection of air pollution control technologies for new source standards development:

- Performance and operating data.
- Reliability of control systems.
- Compatibility with other systems.
- Applicability of control systems to different boiler sizes and types.
- Estimated capital and operating cost of the control systems.
- Control system cost as a function of removal efficiency.
- Status of development.
- Commercial availability.
- Energy requirements of the control system.

The S control options evaluated in this study included PCC and CCC. For PCC, the following types of coals and levels of cleaning were considered.

Coal Type	Control Technology
High S eastern	PCC Level 5-Deep cleaned middlings
Medium S eastern	PCC Level 3
Low S eastern	PCC Level 4
Low S western	PCC Level 2

For the evaluation of CCC, the Meyers, Gravichem, and ERDA processes were selected.

Although the control technologies could be used in combination, they were considered separately for comparison in this study. Final evaluations were based on projected emissions from a set of five reference boilers using four reference coals. The coal-fired boilers chosen for this study and their respective heat input are:

Boiler Type	Thermal input, MW (10 ⁶ Btu/h)
Package, watertube underfeed	8.8 (30)
Field-erected, watertube, chain grate	22.9 (75)
Field-erected, watertube, spreader	44.0 (150)

Field-erected, watertube, pulverized coal 58.6 (200)

Field-erected, watertube, pulverized coal 118.0 (400)

For this study, five emission levels were chosen:

- Stringent-516 ng SO₂/J (1.2 lb SO₂/10⁶ Btu).
- Intermediate-645 ng SO₂/J (1.5 lb SO₂/10⁶ Btu).
- "Optional" moderate-860 ng SO₂/J (2.0 lb SO₂/10⁶ Btu).
- Moderate-1,290 ng SO₂/J (3.0 lb SO₂/10⁶ Btu).
- A State Implementation Plan (SIP) level of 1,075 ng SO₂/J (2.5 lb SO₂/10⁶ Btu).

Equipment and process data compiled previously were used to project the results of applying certain cleaning processes to the reference coals.

Based on performance, cost, energy requirements, and environmental impacts, five best systems of emission reduction were chosen from the original approximately 17 options. The final choices are summarized in Table 4.

Chemical Coal Cleaning

Recognizing the importance of CCC as a potential SO₂ pollutant control option, EPA directed a study in 1977 to investigate the technical and economic feasibility of developing CCC.

The objective of the study was to survey the field of CCC, to identify active and inactive processes, and to perform a critical evaluation of competing processes. The purposes of this evaluation were fourfold:

- To provide updated information on technical and economic viability of these processes and to identify their developmental stage.
- To examine their performance characteristics and environmental aspects.
- To develop quantifiable technical and economic parameters for purposes of process comparison.
- To identify specific research and development needs for processes showing a potential for substantial reduction of S in coals.

Twenty-nine CCC processes were identified for study. Eleven U.S., Japanese, and Australian processes were judged to deserve no further consideration, because they were inactive or proved to be inapplicable to most

U.S. coals. Seven U.S. and Canadian processes were considered to be of minor relevance, because of their early stage of development or inactive status. Eleven U.S. processes were considered to be of major relevance, and these were evaluated in detail with respect to: description; developmental status; technical evaluation, including S removal potential, S by-products, benefits analysis, environmental aspects, and research and developmental efforts and needs; and economics.

Five basic reactions were involved in desulfurization by major CCC processes: oxidative leaching, hydrogen leaching, alkali leaching, chlorine substitution, and iron adsorption. One additional technique was a chemical fracturing step that prepared the coal for desulfurization by conventional PCC.

Detailed comparisons were made on the basis of a common coal feed of Pittsburgh seam bituminous coal. In addition to costs, the following parameters were evaluated:

- Weight yield of cleaned coal based on a common feed coal rate.
- Weight percent S in the cleaned coal product based on the S removal efficiency of the process.
- Heating value yield of the process based on feed coal heating value and the net energy recovery.

SO₂ emission levels were calculated for the cleaned coal products. Emission levels for processes which removed both types of S were below 520 ng SO₂/J (1.2 lb SO₂/10⁶ Btu). Of the four processes which removed only pyritic S, the two that used chemical removal methods (Meyers and LOL) were very close to compliance with 520 ng SO₂/J, but the two processes that used mechanical removal (Syracuse and Magnex®) could only reach an emission limit of 1040 ng SO₂/J (2.4 lb SO₂/10⁶).

Estimated energy recoveries were generally greater than 90% except for the IGT process which was low with 57% recovery. All energy recoveries reflected both the coal loss from processing and the coal used to provide in process heating needs. However except for the IGT process, the actual coal loss from processing was claimed to be small. For most processes, the major heating value loss was due to the use of cleaned coal for in-process heating.

CCC processes were still under development at the time of this study; therefore, the economic evaluations were

Table 4. Best Systems of Emission Reduction for Four Candidate Coals and Five SO₂ Emission Control Levels

Coal	Moderate 1,290 ^a (3.0)	SIP ^b 1,075 (2.5)	"Optional" Moderate 860 (2.0)	Inter- mediate 645 (1.5)	Stringent 516 (1.2)
High S Eastern	PCC Level 5 Middlings	PCC Level 5 Middlings	PCC Level 5 "Deep Cleaned"	PCC Level 5 "Deep Cleaned"	CCC-ERDA
Medium S Eastern	Raw Coal	PCC Level 3	PCC Level 3	CCC-ERDA	CCC-ERDA
Low S Eastern	Raw Coal	Raw Coal	Raw Coal	PCC Level 4	PCC Level 4
Low S Western	Raw Coal	Raw Coal	Raw Coal	Raw Coal	Raw Coal

^ang SO₂/J (lb SO₂/10⁶ Btu).

^bState Implementation Plan.

best engineering estimates based on the information available. Capital and annual operating costs for each major CCC process were estimated. These were based on an assumed plant feed capacity of 7,200 metric tons (8,000 tons) per day, equivalent to the coal needed to fuel a 750 MW electric power plant. The total annual operating costs for each process, including and excluding cost of the raw coal, were also expressed in terms of dollars per metric ton and dollars per 10⁹ calories heat content in the coal. Annual operating costs in 1978 \$, including raw coal cost, ranged from \$43.10 to \$72.50 per metric ton (\$39.10 to \$65.80 per ton) or \$5.32 to \$11.20 per 10⁹ cal (\$1.34–\$2.82 per million Btu).

In general, pyritic S removal processes required the least amount of capital and had the lowest operating costs, but they had limited S removal efficiencies.

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*The complete report, entitled "Assessment of Coal Cleaning Technology: Final
Report," (Order No. PB 87-120 515/AS; Cost: \$24.95, subject to change)
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