United States
Environmental Protection
Agency

Region V
Air & Radiation Branch
230 S. Dearborn Street
Chicago, Illinois 60604

EPA 905/2-83-001
June 1983

EPA

The Impact of Coal Cleaning as a Sulfur Reduction Strategy In the Midwest

THE IMPACT OF COAL CLEANING AS A SULFUR REDUCTION STRATEGY IN THE MIDWEST

by

R.D. Doctor, J.L. Anderson,
D.B. Garvey, C.D. Livengood, and P.S. Farber

EPA 905/2-83-001
ANL/ECT-TM-7

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

IAG No. AD89F2A161
Project Officer: Rizalino Castanares

June 1983

prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
REGION V
Air Management Division
230 South Dearborn Street
Chicago, Illinois 60604

ACKNOWLEDGMENTS

The authors gratefully acknowledge the valuable contributions of the EPA project officers, John Paskevicz and Rizalino Castanares, to the planning and performance of the work presented in this report. Thanks are also extended to B.C. O'Meara and L.S. Benson of Argonne for their preparation of the printed text.

CONTENTS

CONTENTS (Cont'd)

FIGURES

TABLES

THE IMPACT OF COAL CLEANING AS A SULFUR REDUCTION STRATEGY IN THE MIDWEST

by

R.D. Doctor, J.L. Anderson,
D.B. Garvey, C.D. Livengood, and P.S. Farber

ABSTRACT

The potential for reduction of sulfur dioxide emissions through coal cleaning is examined for electric-utility power plants in the Ohio, Indiana, and Illinois region. Twenty-four plants burning predominantly high-sulfur coal and having capacities of 500 MWe or greater are identified, and the characteristics of their coal supplies are analyzed. The sulfur reductions attainable via coal cleaning for the various coals are estimated, and the costs are compared with those for equivalent sulfur dioxide reductions using flue-gas desulfurization. Coal cleaning is shown to be a cost-effective option for approximately half of the plants studied, although the total sulfur dioxide reduction potential is much less than for flue-gas desulfurization.

Regulatory and institutional considerations relevant to mandatory coal cleaning requirements are evaluated, as are options for encouraging greater voluntary use of cleaned coal. Actions at the state level to promote greater use of cleaned coal are found to be most likely.

1 INTRODUCTION

Reduction in sulfur dioxide (SO_2) emissions from stationary sources has long been one of the most prominent objectives of pollution-control legislation and regulation. Emphasis at the federal level has been on developing requirements for new coal-fired power plants and industrial boilers, but the possible impacts of emissions from existing facilities has recently been given new importance in the continuing studies of acid-rain causes and effects. Many such facilities are operating under emission regulations much less stringent than those for new boilers and can be expected to continue in operation for a number of years. This is particularly true in light of the recent slowdown in new power plant construction. Thus, any strategy for regional or national reductions in SO_2 emissions must consider options for increased control of existing sources.

This study had as its primary focus the question of what SO_2 reductions could be obtained in the Midwest by applying extensive physical coal cleaning (PCC) to fuels being burned by major power plants. In addition, we examined briefly the cost tradeoffs betwen coal cleaning and partial flue-gas desulfurization (FGD), as well as the legislative/regulatory options available for implementing a requirement for coal cleaning.

The study involved 24 power plants in Illinois, Indiana, and Ohio that have capacities of at least 500 MWe, burn coal with more than one percent sulfur, and have no FGD systems. We examined the Federal Energy Regulatory Commission (FERC) records (form 423) of 1980 coal purchases for these plants to determine the states, counties, and mine seams that were the sources of the principal coals supplied to each plant. After making these determinations, we used the coal-cleaning ("washing") characteristics of these coals (as previously determined by the U.S. Bureau of Mines) in conjunction with a PCC computer code to model the results of coal washing for these plants. All but one of the coals surveyed showed some reduction in total sulfur content with cleaning. These reductions varied from 0-50%, with an average value of 29%.

The costs of equivalent sulfur dioxide reductions by means of PCC and FGD were estimated and compared on the basis of dollars per ton of SO_2 removed. The results indicate that PCC is the most cost-effective control option for about half of the plants. However, it must be noted that FGD has a greater total potential for SO_2 control due to the higher removal efficiencies possible with currently available technology.

Another factor that makes evaluation of the study results difficult is that most of the coals studied appear to already be receiving some degree of cleaning. Since this information is not reported by the utilities, we inferred the use and degree of cleaning through analysis of raw and delivered coal characteristics together with information on cleaning equipment available at specific mines. Considerations, aside from environmental concerns, that promote the use of cleaning include the large quantities of refuse produced by certain mining techniques, high shipping charges that make preshipment removal of mineral matter (ash) desirable, and plant operational benefits attributable to cleaner and less variable coal. PCC has already achieved wide acceptance, although the high degree of cleaning observed in this study is usually only applied to metallurgical coals. Thus, the potential SO_2 reduction achievable by mandatory PCC is actually somewhat less than projected in this report, by an amount corresponding to current washing practices.

Many plants also fire a variety of coals, some of which differ substantially in sulfur content from the principal coals analyzed in this study. Thus, actual emissions may differ significantly from those predicted on the basis of a single coal per plant. However, while this fact and the current use of coal cleaning may make development of a suitable control strategy more challenging, they should not obscure the conclusion that PCC can make a significant and cost-effective contribution to SO_2 control for many facilities in the Midwest.

Chapter 2 of this report gives the criteria used in selecting power plants for this study and summarizes the plant characteristics, fuel characteristics and sources of data. Chapter 3 presents descriptions of current PCC and FGD technology, while Chapter 4 presents the study results and compares the two approaches to SO_2 control. Policy issues and the conclusions drawn from the results are given in the final two chapters.

2 POWER PLANTS IN THE STUDY REGION

2.1 SCREENING CRITERIA

Criteria for screening power plants in the study region included size, fuel, fuel sulfur content, and current emissions control technologies. Table 1 lists the 24 plants chosen for study as a result of this screening.

The specific screening criteria were:

- Survey region: Illinois, Indiana, and Ohio
- Power-plant size: 500 MW or greater
- Fuel: Coal with a sulfur content exceeding 1%
- Emissions control technologies: Power plants or individual units with FGD systems were eliminated from consideration.

2.2 CHARACTERISTICS OF PLANTS

The breakdown of power plants with coal-firing capacities in excess of 500 MW and no FGD capacity (or FGD capacity limited to recently constructed units) is shown in Table 1. Twenty-four plants were identified, of which only five were of less than 1000 MW capacity and only four were greater than 2000 MW. The typical power plant therefore falls in the range of 1000-2000 MW. The states rank as follows: Ohio - eleven plants, Indiana - nine plants, Illinois - four plants. For purposes of this study, these plants have been randomly ascribed identifying letters, which will be used for the remainder of the report.

2.3 CHARACTERISTICS OF FUEL SUPPLIES

2.3.1 Data Sources

Public utilities are required to file monthly statements with the Federal Energy Regulatory Commission describing the sources of their coal. This one-page form, FERC-423, requests information about the state, county, and name of the producing mine; coal quantities purchased; and the heating value, ash, and sulfur content of the coal. This information is part of the public record of utility activity that is available to any interested party at either the regional FERC offices or the main office in Washington, D.C. The Energy Information Agency (EIA) regularly abstracts the information from these forms relating to coal quantity purchased, heating value, ash, and sulfur content. These computer files were also available to this study.

Table 1 Power Plants with Coal-Firing Capacities of 500 MWe or Greater[a]

State	Plant Names	Unit Numbers	Total Capacity (MWe[b])	Utility
Illinois	Coffeen	1,2	1006	Central Ill. Public Service Co.
	Kincaid	1,2	1319	Commonwealth Edison
	Joppa Steam	1-6	1098	Electric Energy, Inc.
	Baldwin	1-3	1892	Ill. Power Co.
Indiana	Petersburg	1-3	1338	Indianapolis Power & Light Co.
	E.W. Stout	5-7,A3,A4	705	Indianapolis Power & Light Co.
	Bailly	7,8	616	Northern Ind. Public Service Co.
	Michigan City	2,3,12	661	Northern Ind. Public Service Co.
	Cayuga	1,2	1062	Public Service Co. of Indiana
	R. Gallagher	1-4	600	Public Service Co. of Indiana
	Gibson	1-4	2672	Public Service Co. of Indiana
	Wabash River	1-6	962	Public Service Co. of Indiana
	Clifty Creek	1-6	1304	Indiana-Kentucky Electric Corp.
Ohio	Cardinal	1-3	1865	Buckeye Power Co.
	W.C. Beckjord	1-6	1221	Cincinnati Gas & Electric Co.
	Miami Fort	5-8	1377	Cincinnati Gas & Electric Co.
	Avon Lake	6-9	1085	Cleveland Elec. Illuminating Co.
	Eastlake	1-5	1257	Cleveland Elec. Illuminating Co.
	Conesville	1-6	2135	Columbus & Southern Ohio Elec. Co.
	R.E. Burger	1-5	546	Ohio Edison Co.
	Sammis	1-7	2304	Ohio Edison Co.
	Kyger Creek	1-5	1086	Ohio Valley Electric Corp.
	Muskingum R.	1-5	1507	AEP: Ohio Power Co.
	J.M. Gavin	1,2	2600	AEP: Ohio Electric Co.

[a]*Inventory of Power Plants in the United States, 1980 Annual*, U.S. Department of Energy Report DOE/EIA-0095 (June 1981).

[b]Nameplate (gross) capacity.

For purposes of all but a very approximate analysis of performance of coal cleaning systems, it is essential that information about the specific seam being mined be obtained. For this study, we manually examined the FERC-423 forms for 1980 and attempted to reconcile those data with industry reference sources[1] to provide the best basis for the washability calculations. Part of this information had already been summarized in another study for plants in Ohio.[2]

The details of this data acquisition, including additional information for the 53 mines it was possible to identify, are summarized in Appendix A.

2.3.2 Coal Washability Data

The coal washability data were derived by integrating coal washability and coal reserves data obtained from the U.S. Bureau of Mines. Two computer programs previously developed by Argonne[3] matched the appropriate entries in each data set and then merged the data. Approximately 18% of the demonstrated coal reserves were matched with washability data. However, about 35% of the reserves that account for 80% of current production were successfully matched.

Specifications as to the location and size of the reserve, and descriptions of the coal with data on selected physical and chemical characteristics were also included. Washability data are presented for three crush top sizes (1.5 in., 3/8 in., and 14 mesh) and several specific gravities. In each case, the values of percent recovery, Btu/lb, percent ash, percent sulfur, lb $SO_2/10^6$ Btu, and reserves available at 1.2 lb $SO_2/10^6$ Btu are given.

2.3.3 Current Status of Coal Washing

Information about the potential ability of any mine to wash coal can be obtained by reviewing the reported information about preparation equipment. However, the coal washing plants produce a variety of products, including a stream of tailings, that are high in sulfur and ash content. Because these tailings are being sold to the utilities in a few cases, the situation can arise where a plant with the capability for a high level of cleaning is in fact selling a coal high in sulfur and ash content to the utility. Levels of cleaning were assigned to the output from each mine based on a comparison of the washability data with the full series of mine shipments during the year.

3 DESULFURIZATION TECHNOLOGIES

Commercially available desulfurization technologies fall into two basic categories. The first of these are techniques, such as physical coal cleaning, that effect the sulfur removal prior to combustion. Although these technologies have been developing for over 100 years, a number of new and commercially significant approaches are being considered.[4] The second class of desulfurization technologies effects the post-combustion control of sulfur dioxide through the use of flue-gas desulfurization, which has been in commercial use at power plants for about 15 years. An overview of these two contrasting methods follows.

3.1 PHYSICAL COAL CLEANING

Physical coal cleaning processes remove clay, shale, and pyrite from run-of-mine (ROM) coals. Cleaning is achieved by grinding the coal to liberate impurities that are not chemically bound and then taking advantage of specific gravity differences between the organic matter that formed the coals (called macerals) and the denser mineral impurities. Sometimes differences in surface-wetting properties between macerals and impurities are used for separation.

General cleaning strategies for plants depend on the desired level of coal cleaning. These levels are assigned as shown in Table 2.

3.1.1 PCC Commercial Technology

PCC plants may involve up to four major subsystems: 1) comminution (size reduction), 2) screening, 3) concentration, and 4) dewatering. These subsystems have to be tailored to the specific coal and desired level of

Table 2 Levels of Physical Coal Cleaning

Level		Weight Yield (%)	Btu Recovery (%)	Reduction	
				Ash	Sulfur
0	No Preparation (ROM)	100	100	None	None
1	Top Size Control	98-100	100	Fair	None
2	Coarse Beneficiation	75-85	90-95	Good	Fair
3	Moderate Beneficiation	60-80	80-90	Good	Fair
4	Full Beneficiation	60-80	80-90	Excellent	Good

cleaning. This requirement contrasts markedly with the general applicability of flue-gas desulfurization.

Comminution

One of the main goals of the crushing operation is to achieve a specified top-size without creating excessive difficult-to-clean fines. The optimum size to which coal is crushed depends on its washability and end-use.

Rotary breakers are most often used for preparation of deep-mined material with a significant amount of roof and floor material. Radial lifting shelves in the unit lift and drop coals as the unit rotates. Stones, shales, logs, and other debris too large to pass through the perforations in the drum are conveniently discarded. Breakers are the lowest in fines production.

Roll crushers squeeze the coal between tooth-covered rollers. They are also low in fines production and are capable of reducing ROM coal to 1 1/2 in. or less.

Hammer mills throw coal against breaker blocks and grate bars until the product is reduced to the size of the grate opening. These machines produce a large quantity of fines in comparison with the above techniques.

Magnets are often included directly after coarse sizing and crushing in the comminution circuit. "Tramp iron" that may be present in the crushed coal is removed by these magnets so that it will not damage downstream equipment.

Screening

Either wet or dry methods may be used to classify coal into different size ranges before introduction to coal-cleaning circuits. Screens remove rocks and foreign material prior to crushing, and later in the circuit other screens are used to separate coal into coarse and fine fractions for marketing or further preparation. For a Level 1 circuit, comminution and screening are the only system operations. More advanced circuits use screening for recovery from heavy-media circuits and dewatering of coarse coal.

Concentration

Concentration is the operation in which the coal and impurities are actually separated. General methods can be classified as water-only, heavy-media, and dry separation. Some specialized fine-coal recovery methods include froth flotation and oil agglomeration.

Jigs are the oldest and simplest of all coal washing devices. Their principal service is on coarse-sized coal, and they remain the most widely used devices in this country. In jigging, a series of pulses (at the rate of one pulse per second) moves up through the coal-filled bath to provide a rough classification of the coal and mineral impurities by density. The denser impurities are drawn off the bottom and discarded, while the top fraction is withdrawn as product coal. These devices produce a large "middling" product, which is either recycled or sent to other concentrating systems.

The concentrating table is widely used for fine-coal cleaning. Tables are large tilted rhomboid-shaped decks with ridges (riffles) that span the table diagonally. Reciprocating motion of the table causes feed material to fan out onto the deck into strata of different density. Tabling concentrates the heaviest and finest of the particles at the bottom of the deck while the lightest and coarsest particles congregate at the top of the deck. This system is particularly applicable for washing soft and friable coals that degrade easily.

Hydrocyclones are separating devices for medium- to fine-sized coal. These devices make use of high centrifugal forces to effect the separation of denser impurities from the coal. Heavy-media cyclones add 325-mesh magnetite to the wash circuit to increase the wash water's apparent density (to a specific gravity, or S.G., of 1.3-1.8), which provides for a finer "cut" on the pyritic impurities. Currently, this represents the most advanced form of physical coal cleaning available. The circuit becomes more complicated by the need to recover magnetite so as to minimize processing costs. The dense-media recovery unit is generally a drum-type magnetic separator that provides for the effective recovery of all but the smallest of magnetite particles.

Froth flotation has come into wide use for the recovery of the heating value of coal fines produced by the comminution step. In contrast to the other concentrating processes, flotation does not use specific gravity as the basis of the separation. The wetting properties of the macerals and the impurities are characteristically different, the ash being hydrophilic (water-attracting) while the macerals are hydrophobic (water-repelling). Blowing fine bubbles of air through the aqueous phase (usually enhanced by surfactants) floats the coal up to the surface for recovery.

While flotation is effective in ash removal, one serious deficiency is its difficulty in selectively rejecting pyrites. The wetting properties of pyrites are similar to those of coal macerals, and it is generally necessary to reclean the froth, with slight modifications of the surface tension, so as to remove the pyrites.

Dewatering

After washing the coal, excess moisture must be reduced to minimize the penalties incurred in decreased heating value of the fuel, increased transportation costs, and handling and shipping problems. The types of equipment used in this service are directly related to the coal grind. They are screens, centrifugal dryers, various types of vacuum dryers, filter presses, belt filters, thermal dryers, and water clarifiers.

3.1.2 PCC Systems Overview

General cleaning strategies for plants depend on which of the following levels of coal cleaning are desired.

1. Run-of-Mine. Level 1 involves no cleaning but reduces ROM coal to user's size specifications, prepares it for shipment, and possibly reduces moisture content (an important consideration for low-rank western coals). Coal prepared in Level 1 facilities may have to be blended with other coals to meet SO_2 emission standards.

2. Coarse-to-Moderate Beneficiation. Levels 2 and 3 use low-efficiency separation devices to process easy-to-clean coals (coarse coal only in Level 2) and therefore should be employed to remove pyritic sulfur from coal that complies or almost complies with SO_2 emission standards.

3. Full Beneficiation. Level 4 makes use of high-efficiency separation methods to clean the +28 mesh size fractions, while the ultrafine coal (-28 mesh) is cleaned using hydrocyclones. Thus, all coal is cleaned at this level.

The coal processing equipment used will vary with coal characteristics and, to a lesser extent, with site-specific constraints that require the development of the most suitable combination of unit operations for each coal-cleaning case. Consequently, very few physical coal cleaning plants are identical, clearly indicating that no standard solution for upgrading coal exists.

Equipment and/or unit operations can be subtracted or added to adapt to changes in the coal characteristics during the life of a plant. It is also possible to convert the plant to another level of physical coal cleaning. This feature allows the construction and operation of low-level cleaning plants that are designed to be changed to higher level plants at a later date. For descriptive purposes, "typical" flowsheets have been developed for the various cleaning levels. The following descriptions are adapted from Ref. 4.

3.1.3 PCC Level 1 System

Coal for power generation is usually shipped in 2 in. or 1-1/2 in. x 0 size ranges, thus necessitating the crushing of oversize ROM coal. The screening and crushing processes to achieve the required size reduction represent the minimal effort in coal preparation practice.

A rotary breaker could be selected to size eastern bituminous coals, because of their hardness and resiliency. The rotary breaker not only reduces the size of the ROM coal, but also allows the rejection of rock (e.g., roof material from underground mines or overburden from surface mines) in the same operation.

An eastern bituminous coal is typically processed for sizing and rock rejection at its respective mine site. A list of major equipment is included (Table 3), and a process flow diagram is shown in Fig. 1.

The coal generally is delivered to the receiving hopper by trucks (when the coal is mined by open pit) or by belt conveyor (when mined by underground methods). The receiving hopper is equipped with grizzly bars to limit the size of the coal pieces entering. The oversize coal pieces are broken to pass through the grizzly or are removed.

From the receiving hopper, the coal is fed by a reciprocating feeder to a stationary grizzly. This grizzly is equipped with parallel bars that divert the +3 in. oversize coal to a rotary breaker. The -3 in. undersize from the grizzly is collected on a belt conveyor. In the rotary-breaker, the +3 in. raw coal is reduced to 3 in. top size. The rotary-breaker product is discharged to a belt conveyor and combined with the grizzly undersize for transportation to a storage silo. The unbroken material leaving the rotary-breaker eye contains shale, or other waste rock and debris, which is collected in a rock bin for disposal by truck.

Before the coal is discharged into the storage silo, it is sampled and weighed. A suspended magnet is provided for the removal of tramp iron.

Table 3 Major Equipment for Level 1 PCC Plant

Quantity	Equipment
(1)	ROM hopper with grizzly bar, 500 tons
(1)	Reciprocating feeder, 60 in. duplex
(1)	Stationary grizzly, 5 ft x 12 ft
(1)	Rotary breaker, 12 ft (diameter) x 28 ft
(1)	Rock bin, 100 tons
(2)	Belt conveyors, 48 in. wide
(1)	Belt scale
(1)	Tramp iron magnet
(1)	Sampling system
(1)	Storage silo, 15,000 tons, 70 ft (diameter) x 200 ft
(1)	Rail scale
(3)	Dust collectors, 21,500 ft^3/min

3.1.4 PCC Level 2 System

Level 2 PCC involves the cleaning of a course size fraction of the raw coal, preceded by a dry screening operation at a screen-opening size that allows the removal of dry fine coal without blinding the screen cloth. Depending on the moisture content of the raw coal, dry screening is usually limited to a minimum opening size of 1/4 in. Larger screen openings of 3/8 or 1/2 in. generally permit more efficient screening and should be used if characteristics of the raw coal allow use of those larger openings without impairing the final product quality. Vibrating screens are required for the dry screening operation.

The preferred method of cleaning the coarse coal fraction is in a jig, which is characterized by high capacity per unit and separation efficiencies that are sufficient for a Level 2 effort.

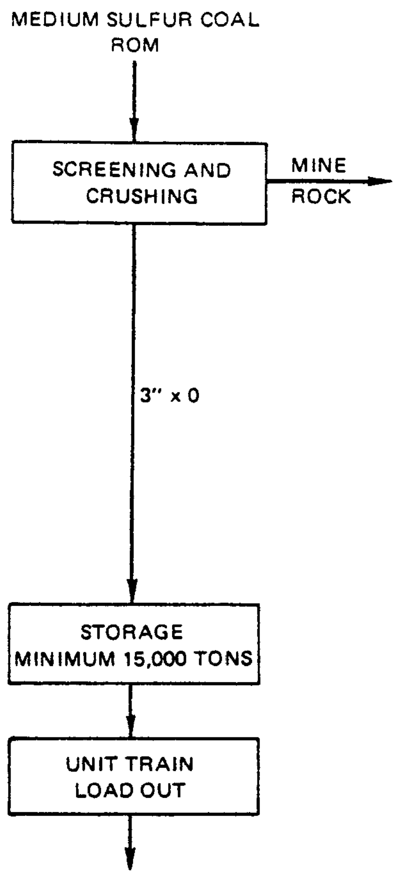


Fig. 1 Block Diagram for Level 1 PCC

Level 2 cleaning is represented by the flow sheet in Fig. 2 and equipment list in Table 4. The ROM coal is delivered to a receiving hopper equipped with grizzly bars to limit the size of coal pieces entering the hopper. The oversize pieces are removed or (if not rock) broken to pass into the hopper. From the receiving hopper, the coal is fed by a reciprocating feeder to a stationary grizzly, which consists of parallel bars to remove the +6 in. oversize coal. The oversize fraction is directed to a rotary breaker for reduction to 6 in. top size. The −6 in. undersize from the grizzly and the crushed coal from the rotary breaker are combined and conveyed to the raw-coal storage silo.

The oversize from the rotary breaker, containing rock or other debris, is collected in a rock bin for transfer into trucks for disposal.

The coal, before being discharged into the raw-coal storage silo, is sampled and weighed. A magnet suspended over the belt conveyor removes tramp iron to provide protection against equipment damage. The storage silo is equipped with hoppers and feeders that permit the withdrawal of coal at a predetermined rate and its discharge onto the plant feed conveyor. This conveyor is equipped with a belt scale to monitor coal feed rate to the plant.

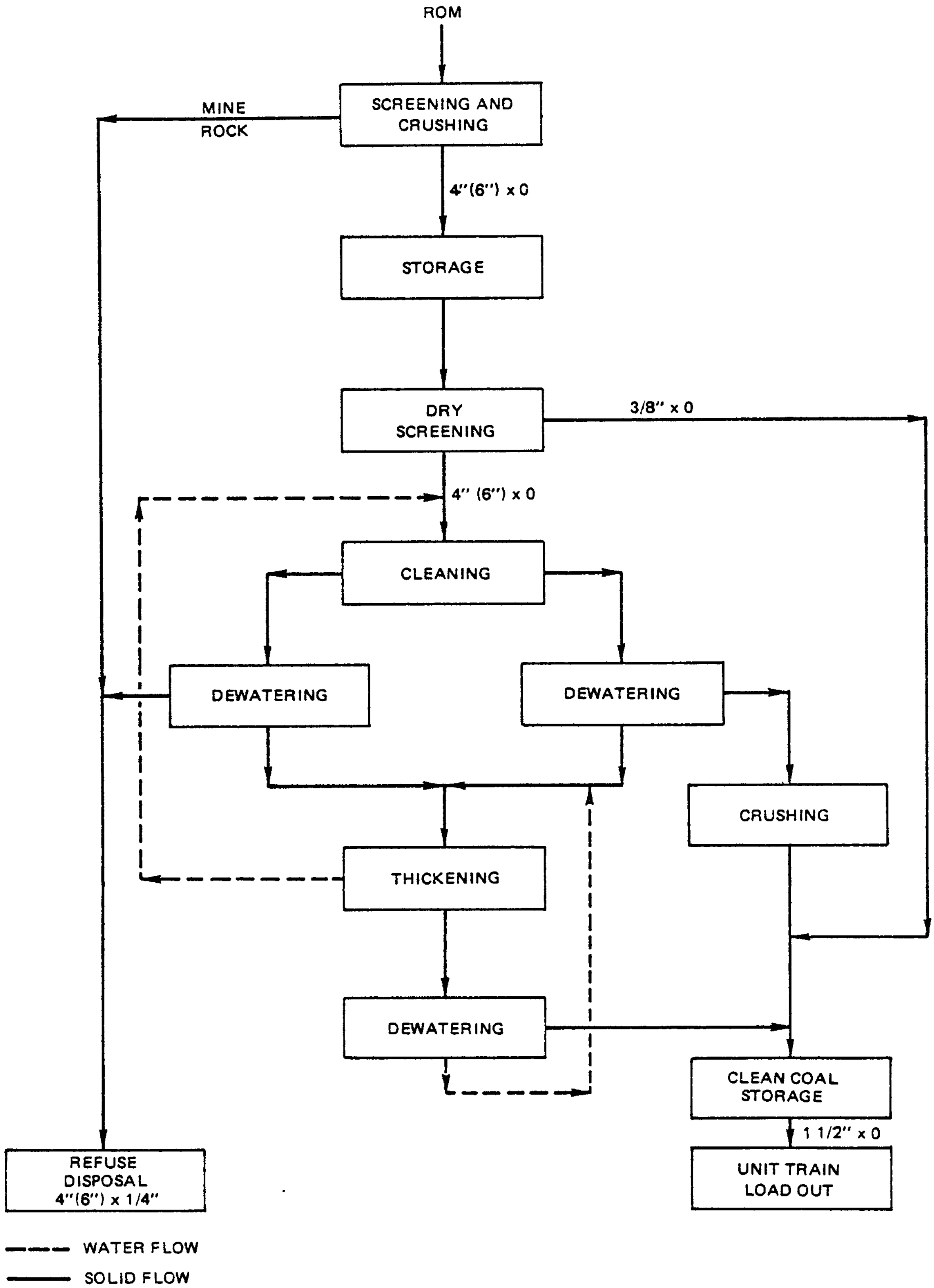


Fig. 2 Block Diagram for Level 2 PCC

Table 4 Major Equipment for Level 2 PCC Plant

Quantity	Equipment
(1)	Hopper bin with grizzly, 500 tons
(5)	Reciprocating feeders
(1)	Vibrating grizzly, 5 ft x 12 ft
(1)	Rotary breaker, 12 ft (diameter) x 28 ft
(1)	Rock bin, 100 ton
(5)	Belt conveyors, 48 in. wide
(3)	Belt scale
(1)	Tramp-iron magnet
(2)	Coal sampling systems
(1)	Raw coal silo, 15,000 tons, 70 ft (diameter) x 200 ft
(4)	Vibrating screen, 8 ft x 20 ft
(4)	Dewatering screens, 8 ft x 16 ft
(1)	Head tank
(1)	Baum jig, two-compartment
(1)	Refuse bin, 300 tons
(4)	Thickening cyclones, 24 ft (diameter)
(1)	Sieve bend, 5 ft wide
(1)	Vibrating centrifuge
(1)	Thickener, 75 ft (diameter)
(2)	Crusher, double roll, 36 in. x 60 in.
(1)	Disc vacuum-filtering system, 12.5 ft (diameter), 13 discs
(2)	Mixing tanks
(1)	Storage silo, 15,000 tons, 70 ft (diameter) x 200 ft
(1)	Rail scale
(1)	Fine coal sump
(2)	Fine coal pumps
(2)	Thickener pumps
(1)	Sump pump
(3)	Dust collectors, 15,000 ft^3/min
(3)	Dust collectors, 21,500 ft^3/min

Upon discharge from the plant feed conveyor, the coal is screened dry on a vibrating screen to remove the oversize, which is sent to be washed. The screen undersize, consisting typically of 3/8 in. x 0 coal, is discharged directly onto the clean-coal collecting conveyor for transportation to the clean-coal storage silo.

The vibrating-screen oversize (typically 6 in. x 3/8 in.) is fed to the washing section. Coal cleaning takes place in a two-compartment Baum-type jig. During the passage of coal through the jig, heavier refuse particles are rejected and conveyed to the refuse bin for disposal. The clean coal is discharged from the jig with the process water and divided into two parallel streams for passage over two vibrating dewatering screens. The dewatered 6 in. x 3/8 in. clean coal continues in two streams to two double-roll crushers for size reduction to 2 in. top size and is then discharged to the clean-coal belt conveyor for transfer to the clean-coal silo. The effluent from the dewatering screens, including some 3/8 in. x 0 solids, is collected in a fine-coal sump and pumped to thickening cyclones, which remove most of the water. The overflow from these cyclones contains coal fines up to 28 mesh. Part of this overflow is used as process water in the jig, while the remainder is directed to a static thickener located outside the washing plant.

The cyclone underflow contains most of the solids, which are dewatered on sieve bends to settle out the -28 mesh solids, the effluent from which is sent to a thickener. The oversize from the sieve bend (3/8 in. x 28 mesh) is further dewatered in vibrating centrifuges and discharged onto the clean-coal conveyor. The effluent of the vibrating centrifuge is also directed to the thickener.

All dilute fine-coal slurry streams from dewatering processes are collected in the static thickener to recover the solids and clarify the water. The recovery process starts with the settling of the solids in the thickener, aided by flocculant. The underflow is pumped to a disc vacuum filter for dewatering of the settled material with the filter cake discharged to the clean-coal conveyor. The clarified overflow from the thickener is pumped to the plant for reuse in the process.

3.1.5 PCC Level 3 System

The PCC Level 3 effort can be considered as an extension of a Level 2 effort in that fine coal cleaning is added to the coarse coal cleaning of Level 2. For Level 3, however, all of the coal feed, including the fines, is wetted (in the Level 2 plant, only the +3/8 in. fraction is washed). Therefore, thermal drying of the fine fraction is an essential part of Level 3. As shown in Fig. 3, ROM coal is delivered to a receiving hopper equipped with grizzly bars to limit the size of the coal entering the hopper. The oversize pieces are removed or broken to pass through the grizzly. The coal is then fed to a stationary grizzly by a reciprocating feeder. The grizzly, equipped with parallel bars, removes the -6 in. coal and discharges the +6 in. coal to a rotary breaker for size reduction below 6 in. The undersize coal from the grizzly and the crushed coal from the breaker are transferred to a belt conveyor and conveyed to the raw-coal silo. The rotary-breaker rejects are transported by a belt conveyor to a rock bin and transported by trucks to a disposal site.

The plant feed belt conveyor accepts the sized coal from the raw-coal silo through reciprocating feeders, and a belt scale monitors plant feed rate.

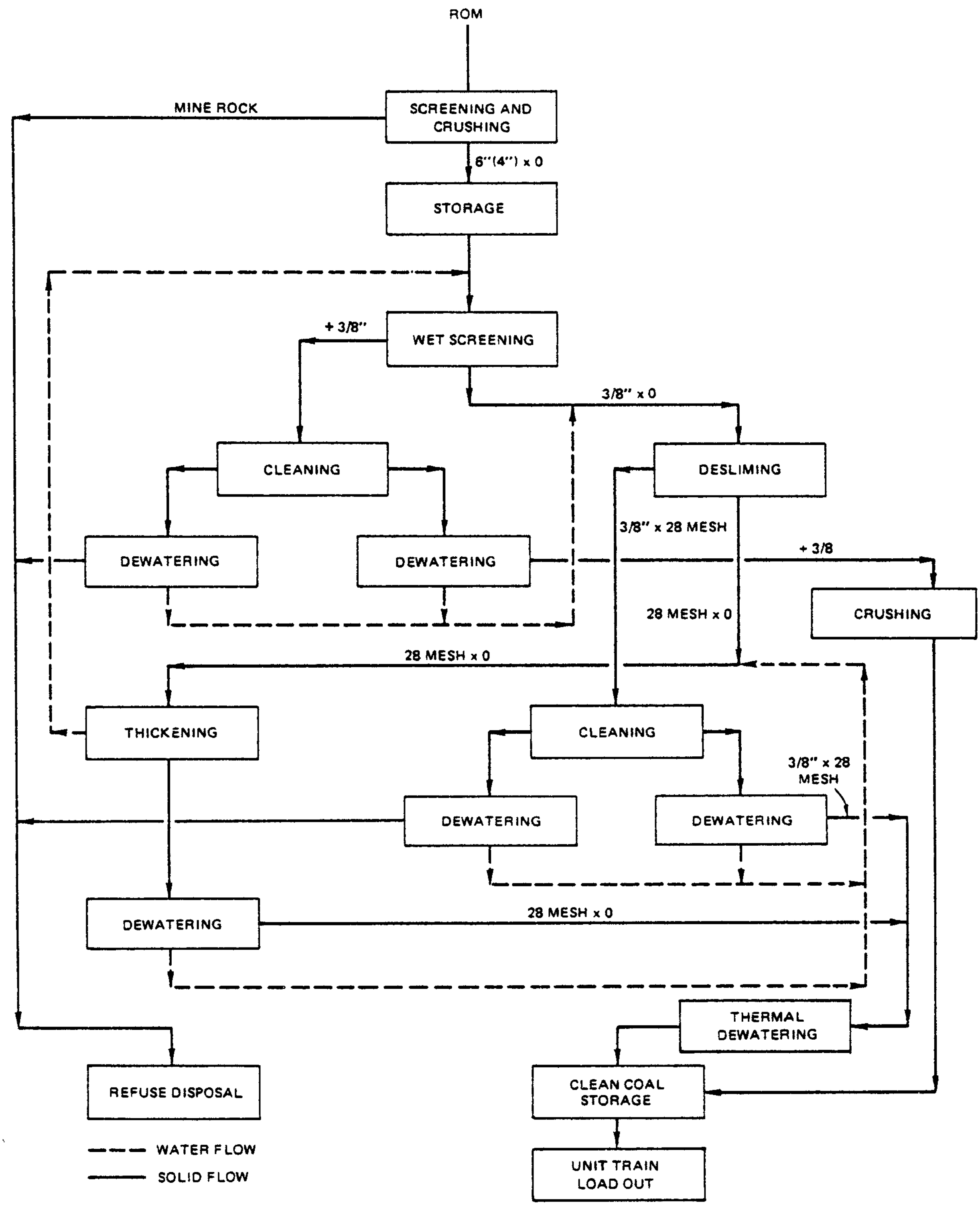


Fig. 3 Block Diagram for Level 3 PCC

The raw coal is discharged to a chute, thoroughly wetted, and screened at 3/8 in. The +3/8 in. coal is sluiced into a Baum-type jig washer. During passage through the jig washer the refuse is separated from the coal and rejected by bucket elevators discharging to a refuse belt conveyor.

The clean coal from the jigs is dewatered on stationary and vibrating screens and classified into two fractions: 6 x 1-1/2 in. coarse coal, which is subsequently reduced to 1-1/2 in. top size in a double roll crusher, and a 1-1/2 by 3/8 in. size fraction that is further dewatered in vibrating centrifuges.

Effluent from the centrifuges and dewatering screens containing -3/8 in. clean coal is combined with the raw 3/8 in. x 0 coal, collected in a fine-coal sump, and pumped to a cluster of six classifying cyclones. Part of the overflow of these cyclones is diverted to a static thickener, while the remaining part is reused as process water in the jigs. The underflow from the cyclones is fed to Deister tables for cleaning. Clean coal is dewatered on sieve bends, screens, and vibrating centrifuges with the effluents from each operation being drained to a static thickener. The dewatered 3/8 in. x 28 mesh fine coal is discharged onto the thermal-dryer feed belt conveyor. Refuse from the Deister tables is dewatered in a spiral classifier and discharged to the refuse belt conveyor. Water (from this operation) containing fine solids is drained to the static thickener.

All -28 mesh fine solids contained in the plant effluents are settled out in the static thickener with the aid of flocculant. The underflow from the thickener is pumped to disc-type vacuum filters, from which the dewatered solids are also fed to the thermal dryer. The filtrate is pumped back to the thickener feedwell.

Clarified overflow from the thickener is collected for reuse in a sump where makeup water is added to balance the plant water circuit.

The thermal dryer receives 3/8 in. x 0 clean coal via belt conveyor at the dryer feed bin. To obtain the specified 6% surface moisture of the total clean coal product, only part of the coal requires thermal drying. Coal drying takes place in a fluidized-bed-type thermal dryer, where a rising current of hot air contacts the coal particles and removes moisture. After drying, the fine coal is combined with the coarse coal. This composite product is sampled, weighed, and transferred to the clean-coal silo.

Table 5 lists the major equipment in the Level 3 PCC plant.

3.1.6 PCC Level 4 System

The flow sheet for Level 4 PCC incorporates heavy medium cleaning processes for the size fractions above 28 mesh. The coarse coal is processed in heavy-medium vessels, whereas the fine coal is treated in heavy-medium

Table 5 Major Equipment for Level 3 PCC Plant

Quantity	Equipment
(1)	ROM hopper with grizzly, 300 tons
(1)	Feeder, 60 in. duplex, reciprocating
(1)	Stationary screen, 5 ft x 12 ft
(1)	Rotary breaker, 12 ft (diameter) x 28 ft
(1)	Rock bin, 100 tons
(5)	Belt conveyors, 48 in. wide
(1)	Belt conveyor, 42 in. wide
(3)	Belt scales
(1)	Tramp-iron magnet
(2)	Coal-sampling systems
(1)	Raw-coal silo, 15,000 tons, 50 ft (diameter) x 120 ft
(4)	Reciprocating feeders
(2)	Jig washers
(4)	Dewatering screens, 8 ft x 16 ft
(6)	Dewatering screens, 6 ft x 16 ft
(1)	Head tank
(6)	Classifying cyclones, 24 in. (diameter)
(6)	Vibrating centrifuges, 36 in.
(1)	Double roll crusher, 36 in. x 60 in.
(2)	Mixing tank
(2)	Disc vacuum-filter systems, 12.5 ft (diameter), 13 discs
(1)	Hammer mill
(1)	Fluidized-bed thermal dryer
(1)	Clean-coal silo, 15,000 tons, 70 ft (diameter) x 200 ft
(1)	Rail scale
(2)	Fine-coal sumps, 2500 gal
(2)	Fine-coal pumps
(1)	Sump pump
(2)	Thickener pumps
(1)	Refuse bin, 300 tons
(2)	Dust collectors, 21,500 ft^3/min
(2)	Dust collectors, 15,000 ft^3/min
(12)	Double-deck Deister tables
(1)	Spiral classifier
(4)	Sieve bends, 5 ft

cyclones or similar devices. The ultrafines are cleaned in two stages of hydrocyclones to maximize pyrite removal and accommodate the cleaning of oxidized coal, which is not possible using froth flotation.

The Level 4 PCC process equipment list is shown in Table 6 with a flow-diagram in Fig. 4. The ROM coal is delivered by trucks or by belt conveyor to a receiving hopper equipped with grizzly bars to limit the size of coal pieces entering the hopper. The oversize pieces are removed or broken to pass through the grizzly. From the receiving hopper the coal is fed by a reciprocating feeder to a stationary grizzly, which consists of parallel bars for the removal of the +4 in. coal. This oversize fraction goes onto a rotary breaker for size reduction. The undersize from the grizzly and the 4-in. top size rotary-breaker product are combined and conveyed to a storage silo. The oversize from the rotary breaker, containing rock or other debris, is collected in a rock bin and transferred to trucks for disposal.

Before being discharged into the raw-coal storage silo, the 4 in. x 0 raw coal is sampled and weighed. A suspended magnet over the belt removes tramp iron for protection against damage to downstream equipment.

The 4 in. x 0 raw coal is delivered to the washing plant by a belt conveyor. The coal is wet-screened at 3/8 in., and the oversize material is fed to a heavy-medium vessel. The design specific gravity of the heavy medium chosen for a typical bituminous coal is 1.40. After separation, the product and refuse are discharged to vibrating screens to remove the heavy medium from the solids and to rinse off magnetite attached to the coal and refuse particles. Double-deck screens are used to classify the clean coal to obtain a 4 x 1-1/2 in. size fraction, which is crushed to minus 1-1/2 in. in a gear roll crusher. The product and rejects are discharged to a clean-coal conveyor and a refuse conveyor, respectively.

The 3/8 in. x 0 slurry from the raw-coal screens is sluiced to vibrating screens preceded by sieve bends and deslimed at 28 mesh. The 3/8 in. x 28 mesh fraction is fed into a sump, mixed with heavy medium, and pumped to heavy-medium cyclones. After separation in the cyclones, heavy medium is drained and rinsed off the products on vibrating screens preceded by sieve bends. The recovered heavy medium is returned to the cyclone feed sump. The clean-coal product is dewatered in a vibrating centrifuge and discharged onto a clean-coal conveyor, which carries the coal to a thermal dryer. After rinsing, the refuse is added to the conveyor with the coarse refuse.

The magnetite-containing effluents from all rinsing screens and the centrifuge are collected in a static thickener to obtain clarified water and an underflow, which is pumped to double-drum magnetic separators. The recovered magnetite is recycled, while magnetite losses are replaced by raw magnetite.

The desliming-screen slurry containing the minus 28 mesh solids is pumped to a two-stage hydrocyclone system. The underflow of the primary

Table 6 Major Equipment List for Level 4 PCC Plant

Quantity	Equipment
(1)	ROM hopper with grizzly, 500 tons
(1)	Reciprocating feeder, 60 in. duplex
(1)	Stationary grizzly, 5 ft x 12 ft
(1)	Rotary breaker, 12 ft (diameter) x 28 ft
(1)	Rock bin, 100 tons
(6)	Belt conveyors, 48 in. wide
(1)	Belt conveyor, 36 in. wide
(3)	Belt scales
(1)	Tramp-iron magnet
(2)	Sampling systems
(1)	Raw-coal silo, 15,000 tons, 50 ft (diameter) x 120 ft
(4)	Reciprocating feeders
(4)	Raw-coal screens, 8 ft x 20 ft
(8)	Sieve bends, 7 ft
(6)	Sieve bends
(2)	Sieve bends, 5 ft
(20)	Dewatering screens, 8 ft x 16 ft
(2)	Dewatering screens, 6 ft x 16 ft
(4)	Heavy-medium vessels, 14 ft wide
(4)	Heavy-medium cyclone, 24 ft (diameter)
(36)	Primary hydrocyclones, 12 in. (diameter)
(18)	Secondary hydrocyclones, 12 in. (diameter)
(1)	Roller crusher, double roll, 36 in. x 60 in.
(1)	Clean-coal silo, 15,000 tons, 70 in. (diameter) x 200 ft
(1)	Rail scale
(1)	Vibrating centrifuge
(2)	Solid-bowl centrifuges
(2)	Vacuum filter, disc systems, 12.5 ft (diameter), 13 discs
(1)	Dilute-medium thickener, 50 ft (diameter)
(1)	Thickener, 190 ft (diameter)
(4)	Magnetic separators, 30 in. x 84 in., double drum
(1)	Fluidized-bed thermal dryer
(1)	Screw feeder, 9 in. (diameter)
(2)	Vibrating feeders
(2)	Heavy-medium sumps
(2)	Fine-coal sumps, 2500 gal
(2)	Cyclone sumps, 950 gal
(4)	Fine-reject sumps, 500 gal
(1)	Heavy-medium storage sump
(4	Thickener pumps
(6)	Sump pumps
(2)	Hydrocyclone pumps
(2)	Heavy-medium pumps
(2)	Flocculant systems

Table 6 (Cont'd)

Quantity	Equipment
(1)	Magnetite storage bin, 100 tons
(2)	Dust collectors, 21,500 ft^3/min
(3)	Dust collectors, 1500 ft^3/min
(1)	Refuse bin, 500 tons

hydrocyclones is diluted with water and reprocessed in the secondary hydrocyclones, where a refuse product is obtained. These rejects are dewatered in solid-bowl centrifuges and disposed of with the other plant refuse.

The secondary hydrocyclone overflow is combined with the magnetic-separator effluent, added to the raw coal, and eventually reprocessed in the first-stage hydrocyclones. The overflow of the primary hydrocyclones containing the clean-coal product is thickened in a static thickener and dewatered in a vacuum-filtration system. The dewatered clean coal is added to the 3/8 in. x 28 mesh clean coal and conveyed to the thermal dryer.

In order to maintain a specified surface moisture of the total clean coal, the 3/8 in. x 0 fraction is thermally dried in a fluidized-bed-type dryer equipped with dry and wet dust-collection sections to obtain acceptable stack-gas emissions. After drying, the coal is combined with the coarse clean coal, weighed, automatically sampled, and discharged into the clean-coal silo.

3.1.7 PCC Existing Capacity

The existing capacity of PCC equipment (effective for Level 2 and higher cleaning) in Illinois, Indiana, and Ohio is displayed in Fig. 5 and given explicitly in Tables 7-9 (based on data from Ref. 1). This inventory shows Illinois with the greatest coal-cleaning capacity, followed by Ohio and Indiana. These figures do not relate the capacity factors for these installations, because that information is not generally reported.

3.1.8 PCC Equipment Service

The issue of physical-coal-cleaning equipment service has not received much attention. In this respect PCC stands in marked contrast to FGD technologies. Failures in operating FGD systems increase sulfur-oxide emissions, while outage times in a coal-cleaning circuit can usually be made up so that the average monthly production of the preparation plant remains constant. Additionally, it appears that many PCC facilities are designed for only

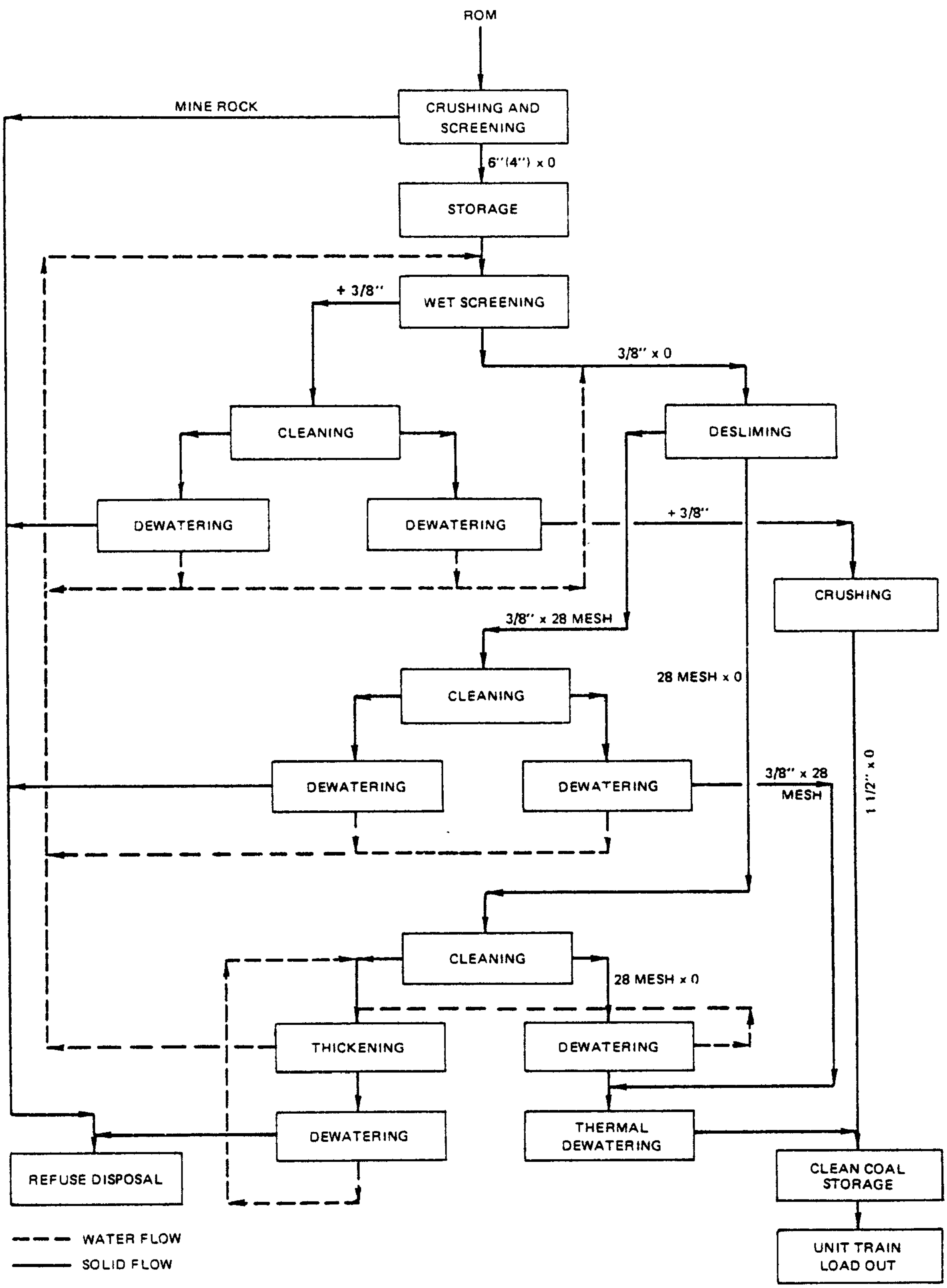


Fig. 4 Block Diagram for Level 4 PCC

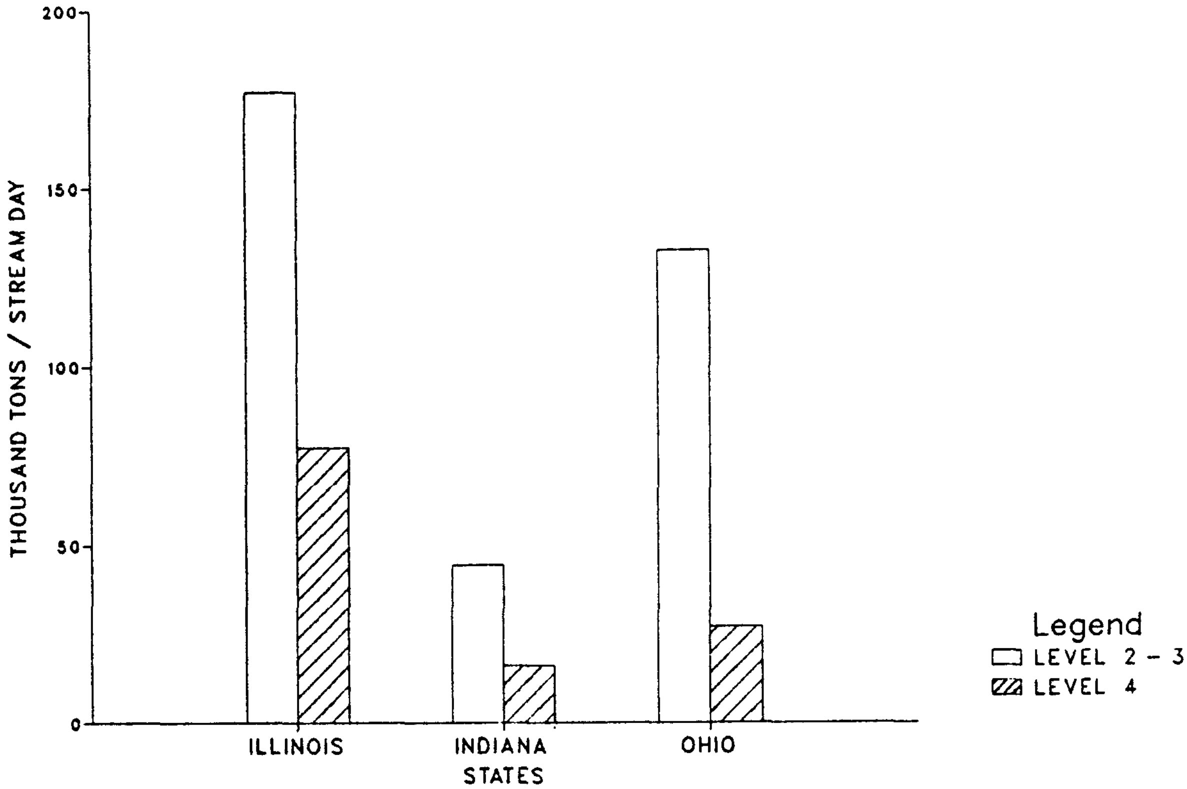


Fig. 5 Physical Coal Cleaning Plants in Illinois, Indiana, and Ohio

single-shift operation, whereas FGD systems must be operated and maintained for the full three shifts during the entire period of the boiler's operation.

3.1.9 PCC Costs

An analysis based on spot market prices for Illinois basin coal in 1982 shows that the market value of coal is still dominated by the heating value, rather than the sulfur content of the coal. This means that in the absence of regulations mandating coal cleaning, the economic incentive for purchasing clean coal will be dominated by the ability of PCC to remove the mineral content of the coal, thus upgrading its heating value. It can readily be shown that at energy recoveries of less than 90%, the process quickly becomes unprofitable. The need to improve energy recovery has been reflected in the PCC industry by the rapid growth of fines-recovery techniques such as froth-flotation.

Additionally, the economic incentive to purchase cleaned coal may be partially credited to avoided utility maintenance costs on items such as coal-handling-and-preparation equipment, boiler-tube fouling, and ash-handling equipment.

Table 7 Inventory of Illinois PCC Plants

			Comminution				Concentration					Dewatering		
Company	Unit Name, Location	Daily Capacity	Breaker	Crusher	Magnet	Screen	Jig	Tables	Cyclone	Heavy-Medium Cyclone	Flotation	Thickener	Dryer	Centrifuge
Amax Coal Co.	Sun Spot Mine, Vermont	3,500	X	X		X			X	X			X	X
Amax Coal Co.	Leahy Mine, Campbell Hill	12,000	X	X		X	X		X					X
Amax Coal Co.	Delta Mine, Marion	4,750		X		X	X		X		X			X
Consolidation Coal Co., Midwestern Region	Burning Star No. 2 Mine, DuQuoin	6,500	X				X						X	
Consolidation Coal Co., Midwestern Region	Burning Star No. 3 Mine, Sparta	6,500	X				X						X	
Consolidation Coal Co., Midwestern Region	Burning Star No. 4 Mine, Cutler		X				X						X	
Consolidation Coal Co., Midwestern Region	Burning Star No. 5 Mine, DeSoto									X				
Freeman United Coal Mining Co., Div. Material Service Corp.	Buckheart Mine 17, Canton	7,000	X	X		X				X				X
Freeman United Coal Mining Co., Div. Material Service Corp.	Orient Mine 3, Waltonville	14,000		X	X	X	X			X	X		X	
Freeman United Coal Mining Co., Div. Material Service Corp.	Orient Mine 6, Waltonville	6,000								X	X		X	
Freeman United Coal Mining Co., Div. Material Service Corp.	Crown II Mine, Virden			X	X	X	X							X

Table 7 (Cont'd)

Company	Unit Name, Location	Daily Capacity	Comminution				Concentration					Dewatering		
			Breaker	Crusher	Magnet	Screen	Jig	Tables	Cyclone	Heavy-Medium Cyclone	Flotation	Thickener	Dryer	Centrifuge
Freeman United Coal Mining Co., Div. Material Service Corp.	Fidelity Mine 11, DuQuoin	7,500					X							X
Freeman United Coal Mining Co., Div. Material Service Corp.	Orient Mine 4, Marion	7,000		X			X			X			X	X
Inland Steel Coal Co.	Inland Mine No. 1, Sesser		X						X	X	X	X	X	
Inland Steel Coal Co.	Inland Mine No. 2, Sesser		X						X	X	X	X	X	
Midland Coal Co.,A Div. of ASARCO, Inc.	Rapatee Mine, Middlegrove		X	X		X	X		X					X
Midland Coal Co.,A Div. of ASARCO, Inc.	Elm Mine, Trivoli	7,000	X	X		X	X		X				X	X
Monterey Coal Co., A Div. of Exxon Coal USA, Inc.	Monterey No. 1 Mine, Carlinville	12,000	X	X	X	X	X		X					X
Monterey Coal Co., A Div. of Exxon Coal USA, Inc.	Monterey No. 2 Mine, Albers	20,000	X	X	X	X	X		X			X		X
Morris, Coal, Inc.	Morris No. 5, Pittsburgh	5,000	X	X	X	X	X		X				X	
Old Ben Coal Co.	Old Ben No. 21, Sesser						X		X	X	X		X	
Old Ben Coal Co.	Old Ben No. 25, Benton		X			X	X		X		X	X	X	X
Old Ben Coal Co.	Old Ben No. 26, Sesser						X	X						
Old Ben Coal Co.	Old Ben No. 27, Benton		X			X	X		X		X	X	X	X

Table 7 (Cont'd)

Company	Unit Name, Location	Daily Capacity	Comminution: Breaker	Comminution: Crusher	Comminution: Magnet	Comminution: Screen	Concentration: Jig	Concentration: Tables	Concentration: Cyclone	Concentration: Heavy-Medium Cyclone	Concentration: Flotation	Dewatering: Thickener	Dewatering: Dryer	Dewatering: Centrifuge
Peabody Coal Co.	Mine No. 10, Pawnee	15,500	X	X		X	X							
Peabody Coal Co.	Eagle Surface Mine, Shawneetown					X	X							X
Peabody Coal Co.	Eagle No. 2 Mine, Shawneetown	10,000					X							X
Peabody Coal Co.	River King U.G. No. 1 Mine, Freeburg	7,000	X	X			X							X
Peabody Coal Co.	Will Scarlet Mine, Stonefort	6,500		X			X						X	
Sahara Coal Co., Inc.	Central Preparation Plant, Harrisburg	12,000							X	X				X
Southwestern Illinois Coal Corp.	Streamline Mine, Percy			X	X	X		X	X				X	X
Zeigler Coal Co.	Murdock Mine, Murdock		X	X	X	X	X							X
Zeigler Coal Co.	Spartan Mine, Sparta	4,000	X	X	X	X	X	X						X
Zeigler Coal Co.	Mine No. 11, Coulterville		X	X	X	X	X	X			X			X

Table 8 Inventory of Indiana PCC Plants

Company	Unit Name, Location	Daily Capacity	Comminution: Breaker	Comminution: Crusher	Comminution: Magnet	Comminution: Screen	Concentration: Jig	Concentration: Tables	Concentration: Cyclone	Concentration: Heavy-Medium Cyclone	Concentration: Flotation	Dewatering: Thickener	Dewatering: Dryer	Dewatering: Centrifuge
Amax Coal Co.	Chinook Mine, Brazil	5,500	X	X		X	X		X				X	X
Amax Coal Co.	Minnehaha Mine, Sullivan	8,000		X		X	X		X					X
Amax Coal Co.	Ayrshire Mine, Chandler	16,000	X	X		X	X		X		X		X	X
Peabody Coal Co.	Hawthorn Mine, Carlisle	5,000		X			X		X					
Peabody Coal Co.	Universal Mine, Universal	6,000	X	X			X		X					
Peabody Coal Co.	Lynnville Mine Nos. 1 & 2, Lynnville	14,000	X	X			X	X	X				X	X
Peabody Coal Co.	Squaw Creek Mine, Boonville	6,000	X	X			X		X				X	

Table 9 Inventory of Ohio PCC Plants

Company	Unit Name, Location	Daily Capacity	Comminution				Concentration					Dewatering		
			Breaker	Crusher	Magnet	Screen	Jig	Tables	Cyclone	Heavy-Medium Cyclone	Flotation	Thickener	Dryer	Centrifuge
Central Ohio Coal Co.	Muskingum Mine, Cumberland	12,000	X	X	X	X	X		X		X	X		X
Consolidation Coal Co., Midwestern Region	Georgetown Preparation Plant No. 19, Cadiz	15,000	X	X	X	X	X	X	X		X			X
East Fairfield Coal Co.	East Fairfield Prep. Plant North Lima	3,600		X	X	X			X			X		X
Holmes Limestone Co.	Preparation Plant Div., Berlin						X							X
Horizon Coal Co.	Bolivar/Strasburg Operation, Zanesville	1,500		X		X	X							X
Horizon Coal Co.	Roseville Operations, Zanesville	1,000		X				X			X			X
Industrial Mining Co.	Rogers Mine, Lisbon	2,500	X	X					X	X				X
Island Creek Coal Co.	Vail Mine (Northern Div.), Freeport		X			X				X		X		X
K&R Enterprises, Inc.	Stark No. 1 & Kefferrose Pits, Canfield			X		X	X		X				X	X
K&R Enterprises,	Keffler Rose Mine No. 2, Canfield			X		X	X		X			X	X	X
Nacco Mining Co.	Powhatan No. 6, Alledonia	11,000				X	X		X			X	X	X
North American Coal Corp.	Powhatan No. 1, Mine, Powhatan Point		X	X		X				X				
North American Coal Corp.	Powhatan No. 3 Mine, Powhatan Point		X			X				X				

Table 9 (Cont'd)

Company	Unit Name, Location	Daily Capacity	Comminution				Concentration					Dewatering		
			Breaker	Crusher	Magnet	Screen	Jig	Tables	Cyclone	Heavy-Medium Cyclone	Flotation	Thickener	Dryer	Centrifuge
North American Coal Co.	Powhatan No. 5, Mine, Powhatan Point						X					X		
Oglebay Norton Co.	Saginaw Mining Co. Mine, St. Clairsville	4,500								X				
Ohio Coal & Construction Corp.	Rayland Plant & Dock (Bargeloading), Wintersville	300		X	X	X			X	X				
Peabody Coal Co.	Broken Aro Mine, Coshocton	8,000					X							
Peabody Coal Co.	Sunnyhill Mine, New Lexington	6,000		X		X	X						X	
Quarto Mining Co.	Powhatan No. 4 Mine, Powhatan Point	7,500		X		X	X		X			X		X
Quarto Mining Co.	Powhatan No. 7 Mine, Powhatan Point	8,400		X			X		X			X	X	X
R&F Coal Co.	Rice 1,2,3,4,5, 6,7,8, Polen, Barb Tipple, Bellaire Dock, Lamira Prep. Plant, Cadiz	15,000	X	X		X			X	X		X		X
Southern Ohio Coal Co.	Meigs Mine No. 1, Athens	18,850	X	X	X	X				X		X		X
Southern Ohio Coal Co.	Raccoon Mine No. 3, Athens	7,000	X	X	X	X	X		X			X		X
Youghiogheny & Ohio Coal Co.	Allison Mine, Beallsville	5,000		X	X	X	X					X		X
Youghiogheny & Ohio Coal Co.	Nelms Mine Cadiz Portal, Cadiz	5,000		X	X	X	X							X

3.2 FLUE-GAS DESULFURIZATION

Most of the FGD systems currently operating in the field represent an early generation, if not the first generation, of their respective technologies. Consequently, there remain uncertainties about costs, materials of construction, and reliability of the units in service. The investment costs, operating costs, and total costs vary significantly, depending on the year of construction, FGD vendor, unit size, fuel burnt, and sludge-disposal methods.

3.2.1 FGD Commercial Technology

Limestone and lime FGD systems can be considered relatively mature technologies that have experienced more than a decade of utility service. Further evolutionary development of the technologies may still be anticipated. Other FGD processes are reaching a point in their development where it is possible to begin assessing their commercial performance in detail. Existing processes include:

- Lime/Limestone
- Lime/Limestone with Adipic-Acid Addition
- Lime/Limestone with Forced Oxidation
- Lime/Limestone with Alkali Fly-Ash Addition
- Lime/Spray-Drying
- Dual-Alkali
- Wellman-Lord
- Sodium Carbonate

The operation of these systems and their ability to control SO_2 emissions have been demonstrated. Current efforts are being directed toward improving the process economics, availability, and sulfur-dioxide-removal efficiency.

Lime/Limestone FGD Systems

The lime and limestone FGD processes are considered as one reference technology, or base case, for the FGD technologies discussed in this report. This method of SO_2 removal has been applied in many coal-fired electric-generating stations, and many more units are in the design or construction phase. Historically, capital investments and operating costs vary greatly from application to application. The different costs reflect significantly different site properties, the sulfur content of the coal used, different SO_2 removal requirements, etc. Major advantages of this base-case technology include the extensive experience gained with it to date and the availability of the materials needed. Disadvantages include a high rate of forced outages, corrosion and erosion problems, and the need to dispose of great quantities of sludge.

Lime/Spray-Drying FGD Systems

The spray-drying/baghouse technology represents an improvement over the dry injection/baghouse process in that (1) sorbents other than (scarce) nahcolite can be used; (2) a somewhat higher SO_2 removal efficiency can be achieved; and (3) depending upon the sorbent used, the waste-disposal difficulties can be significantly reduced. In principle, this technology, which has been commercially applied at both utility and industrial facilities, can be used with all types of coal. However, economic considerations are still being evaluated for its application to coals with a sulfur content of greater than 2.5-3%.

Dual-Alkali FGD Systems

Dual-alkali scrubbing is a wet, regenerable process combining absorption of SO_2 (with an aqueous alkali solution) and regeneration of the absorbent (with lime). The dual-alkali systems utilize a clear sodium-sulfite-based absorption solution. Compared with lime/limestone systems, they have reduced problems with plugging, scaling, and erosion. Existing systems remove SO_2 with 90-95% efficiency. Although some systems have had mechanical or chemical problems, they have shown themselves reliable; less than 10% of their total operating time has been interrupted with forced outages. This FGD technology has good retrofit potential, based on the small size of its components. The process does require a large land area for disposing of the solid waste it generates. Economically, dual-alkali systems appear to be competitive with the wet lime and limestone systems. The process has been commercially applied in the U.S. Three full-scale demonstration systems are operating with coal-fired utility boilers, and several commercial units are in operation with coal- and oil-fired industrial boilers. Further development work is needed to evaluate, characterize, and compare full-size coal-fired demonstration facilities; to test systems using limestone as a regenerant; and to develop methods for upgrading the quality of sludge.

Wellman-Lord FGD System

Wellman-Lord is an aqueous process that employs a sodium-sulfite scrubbing solution to remove SO_2 from flue gas. Thermal regeneration enables the system to recover the sulfite and produce a concentrated stream of SO_2. This process has been applied commercially both in the U.S. and overseas to desulfurize flue and waste gases from oil- and coal-fired boilers, nonferrous smelters, sulfuric-acid plants, and Claus plants. This FGD process has all of the advantages associated with sodium-sulfite-based scrubbing: a high SO_2 removal efficiency, no plugging or scaling in scrubbing, and a low liquid-to-gas ratio. It is a closed-loop operation, producing marketable end products with no large-scale solid-waste disposal problems. The regeneration loop is a complicated process requiring a relatively high energy input and relatively higher capital and operating costs than throwaway processes. Further development is needed to investigate specific process improvements, to evaluate the process performance in full-scale demonstrations with coal-fired boilers, and to test the Wellman-Lord system in combination with downstream sulfur-reduction systems, particularly those using coal as a reducing agent.

Sodium-Carbonate FGD System

The aqueous-carbonate process combines the spray-dryer technology with methods of regenerating the sorbent material and producing a marketable end product with the sulfur removed from the flue gas. This FGD technology can therefore greatly reduce the amount of sorbent (Na_2CO_3) required and can also produce revenues that partially offset its own costs. Regeneration and sulfur-recovery techniques make the system complex, however, and this complexity raises both investment costs and operating and maintenance costs. On the other hand, SO_2 removal efficiencies can potentially exceed those that are possible with other advanced FGD technologies. A 100-MW test facility is currently under construction.

One major issue of considerable importance to the further use of this technology is the sludge-disposal problem associated with FGD. Over the next few decades, there will be increasing problems with siting landfills for the solid wastes continuously generated by coal-burning facilities. Precombustion removal of ash and sulfur through PCC could help ease this problem.

3.2.2 FGD Existing Capacity

The deployment status of FGD technology and its relation to coal sulfur content can be seen in Fig. 6. Not shown in this figure are the relative capacity factors for the various systems. If this consideration were included, the role of scrubbing would be reduced, although the high-sulfur component would be reduced more significantly than the low- and medium-sulfur components.

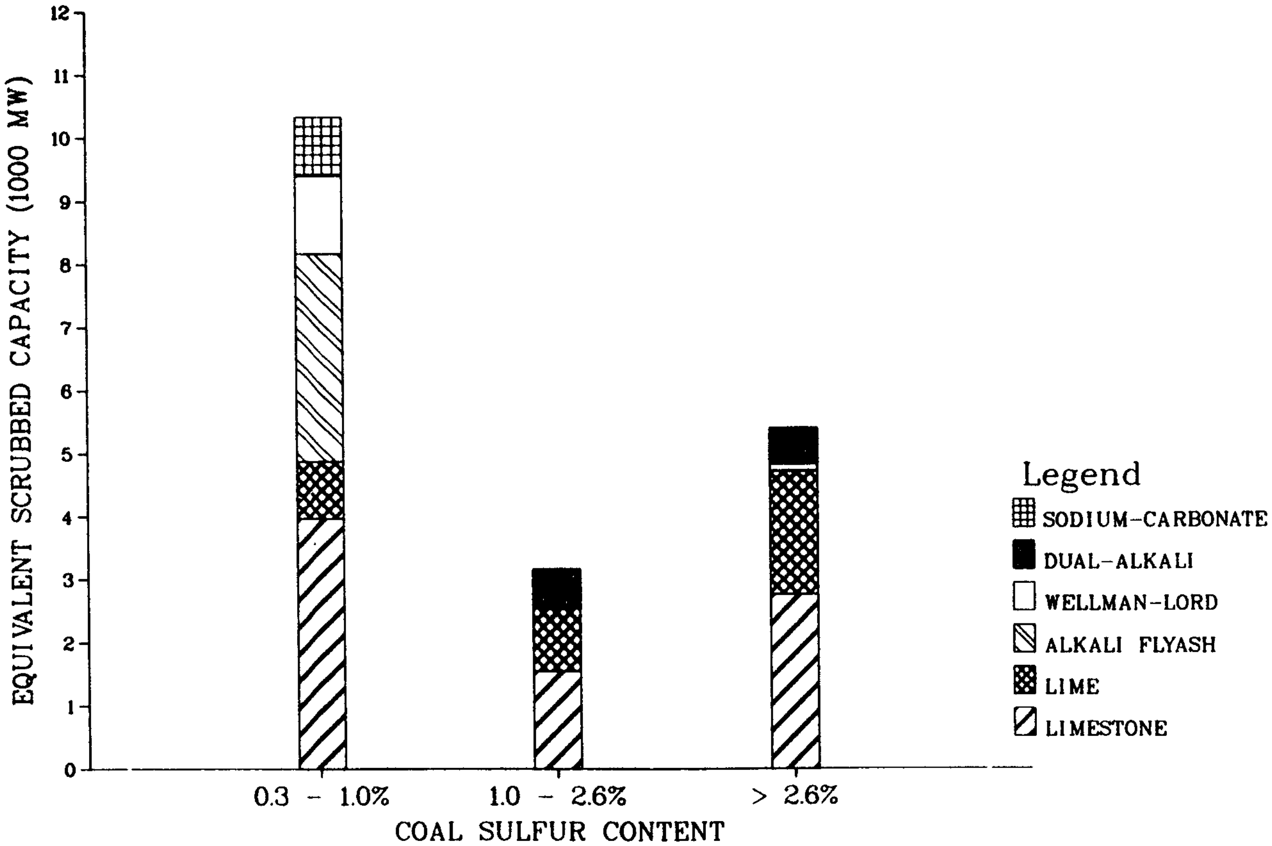


Fig. 6 Coal Sulfur Content vs. Equivalent Scrubbing Capacity, 1980
(Source: Ref. 5)

3.2.3 FGD Equipment Service

The results of a recent Argonne study[5] on FGD system availability appear in Fig. 7. In this study, the system availability was correlated with the inlet concentration of SO_2 and design scrubbing efficiency (which are related to system size and sorbent utilization). The trends indicate that all the technologies exhibit high availability when used in low-sulfur-coal applications, but availability decreases for high-sulfur-coal applications.

As the coal sulfur content increases to 3.5% and the required removal efficiency increases, dual-alkali systems maintain system availabilities of 80% or higher, while all the lime/limestone FGD systems show marked declines in availability. The problems with water chemistry are apparently compounded by closed-water-loop operations (where the operation minimizes the make-up water needed to produce fresh scrubbing liquor by recycling as much water as possible from other stages of the operation), and these systems exhibit system availabilities much lower than the open-water-loop systems. Adipic acid leaves this trend unaffected, although alkali-ash addition makes it much worse.

The Wellman-Lord system has an apparent advantage over lime/limestone systems for high-sulfur coals at high removal efficiencies. The system availability exhibited by this system is interpreted as falling off at nearly the same rate as for dual-alkali systems, but at an availability lower by a constant factor. This may be attributed to the overall increased complexity of the system, especially the regeneration loop.

3.2.4 FGD Costs

Capital and annual cost data for operational FGD systems have been obtained continuously since March 1978 for the EPA.[6] Costs for each system are obtained directly from the utilities and then itemized by individual FGD cost elements. The itemized costs are then adjusted to a common basis to enhance comparability. This adjustment includes estimating costs not given by the utilities and escalating all costs to common dollars (mid-1981). All adjusted cost data and computations are reviewed and verified with the appropriate utility before publication.

The key factors used to produce these cost adjustments are:

Capital Costs

- All costs associated with control of particulate-matter emissions are excluded.

- Capital costs for modifications necessitated by installation of an FGD system are added if they were not included in the reported costs.

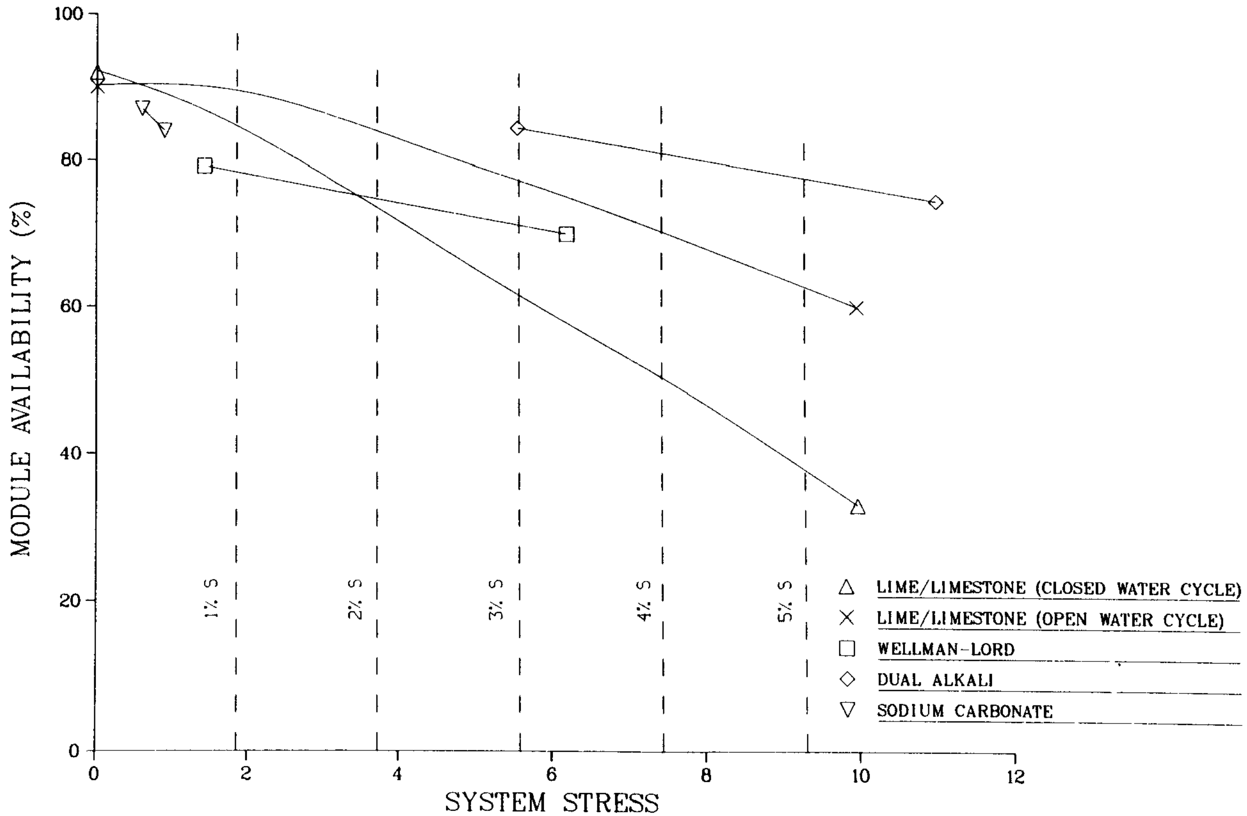


Fig. 7 Summary and Comparison of Calculated FGD System Availabilities (Source: Ref. 5)

- Sludge disposal costs are adjusted to reflect a 20-year life span for retrofit systems and a 30-year life span for new systems.
- Any unreported direct and indirect costs incurred are estimated and included.
- All capital costs are escalated to mid-1981 dollars.
- All $/kW values reflect the gross generating capacity of the unit.

Annual Costs

- All costs are adjusted to a common 65% capacity factor.
- Direct costs that were not reported are estimated and added.
- Overhead and fixed costs that were not reported are estimated and added.
- All annual costs are escalated to mid-1981 dollars.
- All mill/kWh values are based on a 65% capacity factor and the net generating capacity of the unit.

A summary of these data (Table 10) shows the cost trends, which provide a fair match with the deployment of existing equipment as outlined in Sec. 3.2.2.

Table 10 Adjusted Capital and Annual Costs for Operational FGD Systems by Process Type

	Reported						Adjusted					
	Capital			Annual			Capital			Annual		
Process Type	Range, \$/kW	Average, \$/kW	σ[a]	Range, mill/kWh	Average, mill/kWh	σ	Range, \$/kW	Average, \$/kW	σ	Range, mill/kWh	Average, mill/kWh	σ
Limestone	23.7–170.4	67.9	37.2	0.1–7.8	1.6	2.2	38.3–194.3	98.9	44.0	1.6–14.6	6.1	3.1
Lime	29.4–213.6	81.8	43.7	0.3–11.3	3.2	2.7	60.4–210.0	116.5	44.2	4.0–17.6	8.1	3.6
Dual alkali	47.2–174.8	97.8	55.3	1.3–1.3	1.3	0.0	87.8–163.9	146.7	82.9	5.0–13.9	8.7	3.8
Lime/alkaline fly-ash	43.4–173.8	93.9	44.0	0.4–5.4	2.1	1.9	52.5–184.4	122.8	51.4	3.0–14.1	7.2	3.8
Sodium carbonate	42.9–100.8	69.2	26.2	0.2–0.5	0.4	0.1	87.1–150.9	110.9	26.4	5.8– 7.4	6.4	0.7
Wellman-Lord	132.8–185.0	153.1	20.6	13.0–13.0	13.0	0.0	254.6–282.2	271.6	12.1	16.7–20.8	18.1	1.9
Limestone/ alkaline fly-ash	49.3–49.3	49.3	0.0	0.8–0.8	0.8	0.0	102.6–102.6	102.6	0.0	5.4– 5.4	5.4	0.0

[a]Standard deviation.

4 COMPARISON OF PCC AND FGD

Assessment of emissions on the basis of pounds of SO_2 per million Btu was necessary for this study. This corresponds to the way most emission regulations are written and avoids difficulties that could occur due to differences in specific mining techniques. For example, it would be necessary to consider the mining technique if the comparison were based on SO_2 emissions per ton of coal. Consider the case of a uniform coal bed that can be strip-mined in one part of a county, while for the remainder of the county the bed must be deep-mined. Strip-mining typically permits rather close control over the quality of the ROM coal, and significant amounts of the shale matrix are excluded from the ROM coal. This is not the case for deep-mined coal. Today, deep-mining of coal is highly automated, and it is common for these automated procedures to include significant amounts of the roof and floor material in the ROM product. If the coals obtained by these two methods were compared on the basis of SO_2 emissions per ton, the outputs of the strip-mine and the deep mine would appear quite different. However, using the heating value (Btu/lb) of the coal as the basis of comparison would yield a single value for the outputs of the two mines. Throughout this study we will continue to use this "Btu" basis rather than "tons of coal."

4.1 EMISSIONS CORRESPONDING TO ROM COAL

Characterizing the emissions corresponding to the ROM coals requires the following data:

- ROM coal characteristics for major coal suppliers to the power plant, or

- "As-received" coal characteristics for the major coals supplied to the power plant, together with a knowledge of the preparation level for the coal.

For the majority of the power plants considered in this study, both of these techniques were used to complement each other. It was possible to identify 53 mines located in Illinois, Indiana, Ohio, Kentucky, West Virginia, or Pennsylvania that served as the principal suppliers to the utilities of interest in Illinois, Indiana, and part of Ohio. Appendix A contains a series of tables with specific data for these mines. A perusal of these data should demonstrate that at least a modest level of coal preparation is typical for coals provided by these principal suppliers. However, it should be remembered that current deep-mining techniques virtually require some coal washing to remove roof and floor materials. This removal is undertaken by the companies for reasons unrelated to environmental concerns about sulfur reduction. Relatively minor sulfur reductions are typical of most cleaning operations employed for steam coal.

The ROM emissions for each power plant's principle coal is rendered graphically for 15 plants in Fig. 8, and for all plants in Fig. 12 to facilitate comparisons with the PCC techniques. One other significant issue was addressed by this study in order to clarify the overall environmental impact of any particular power plant. This is to link the SO_2 emissions per million Btus with a plant capacity factor to calculate the thousands of tons of SO_2 per year that a specific power plant would be expected to generate (see the explanation of Fig. 9 that follows).

4.2 EMISSIONS UNDER 1980 CONDITIONS

In order to determine power-plant SO_2 emissions for 1980, it was necessary to analyze the monthly Form 423 data that each utility provides to the FERC. For each coal purchase, the utility supplies FERC with coal quantity purchased; heating value; ash content; sulfur content; and state, county, and name of the producing mine (see Appendix A).

By reviewing the coal-cleaning equipment available to each supplier, it was possible to assign approximate coal-cleaning levels to each producing mine. These levels were:

- ROM (PCC Level 1),
- Coarse-to-moderate cleaning (PCC levels 2 and 3), and
- Full beneficiation (PCC level 4).

These levels are the same as those referenced in Sec. 3.1.2.

Power-plant SO_2 emissions in pounds of $SO_2/10^6$ Btu (Fig. 8) and overall SO_2 emissions for 1980 in thousands of tons (Fig. 9) were calculated for each utility by using a computer program to merge coal suppliers' cleaning-level data with coal purchase data from the Form 423 file. No credit was taken for sulfur removed with the boiler bottom ash. This is typically 5% of the total sulfur. Figure 9 shows which plant/coal combinations actually account for the greatest SO_2 emissions. These estimates are the multiplicative products of SO_2 emissions rate, power-plant size, and power-plant capacity factor.

4.3 PURCHASE PATTERNS FOR COAL IN 1980

Several trends were noted in the utility coal-purchase patterns for large and small coal purchases. The purchase-pattern trends are related here, because they may bear on future deployment of PCC systems. The trends are:

- Mine-mouth power plants typically make modest purchases each month from other mines in addition to their major purchase from the adjacent mine.

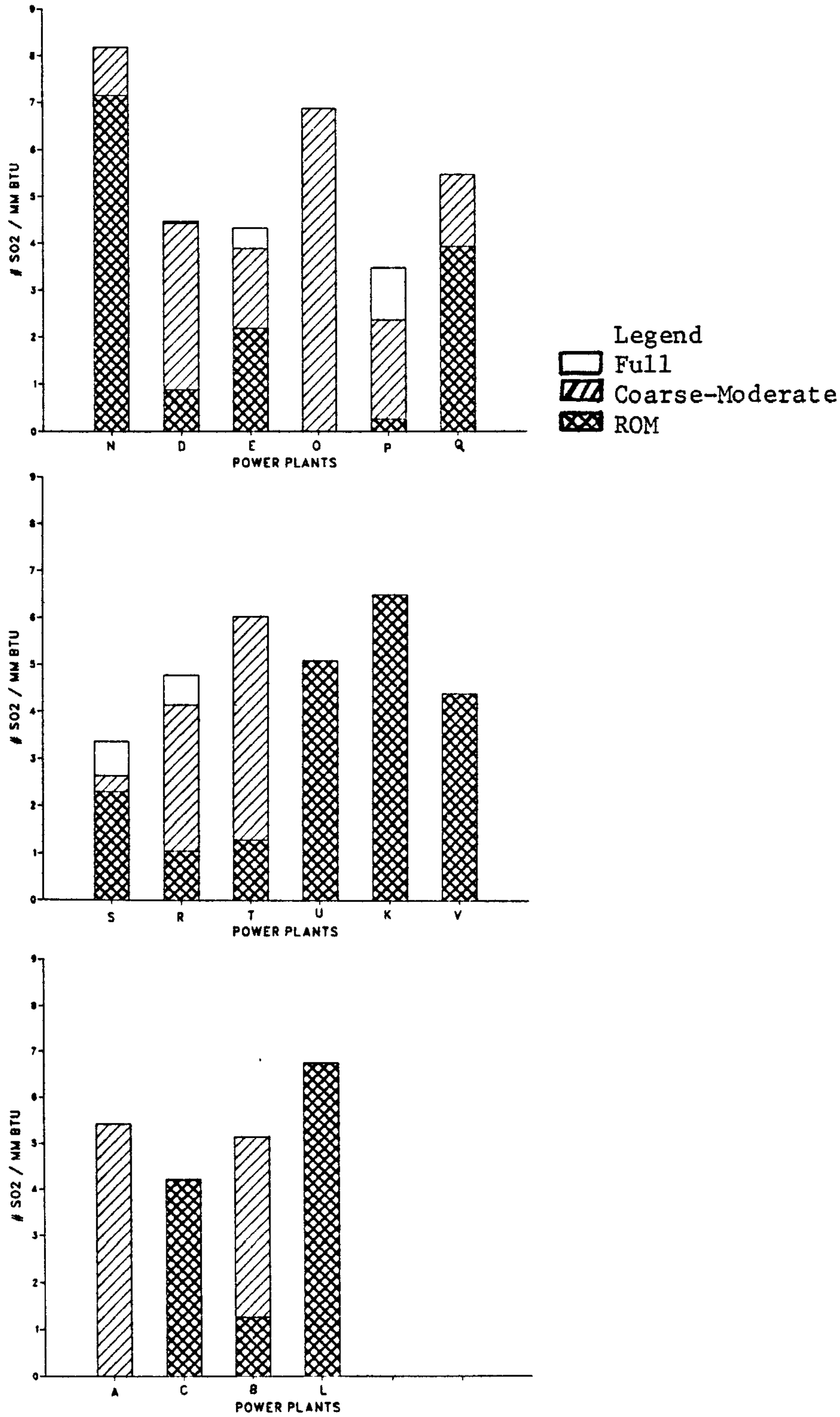


Fig. 8 Power-Plant SO_2 Emission Rates, 1980 (lb $SO_2/10^6$ Btu)

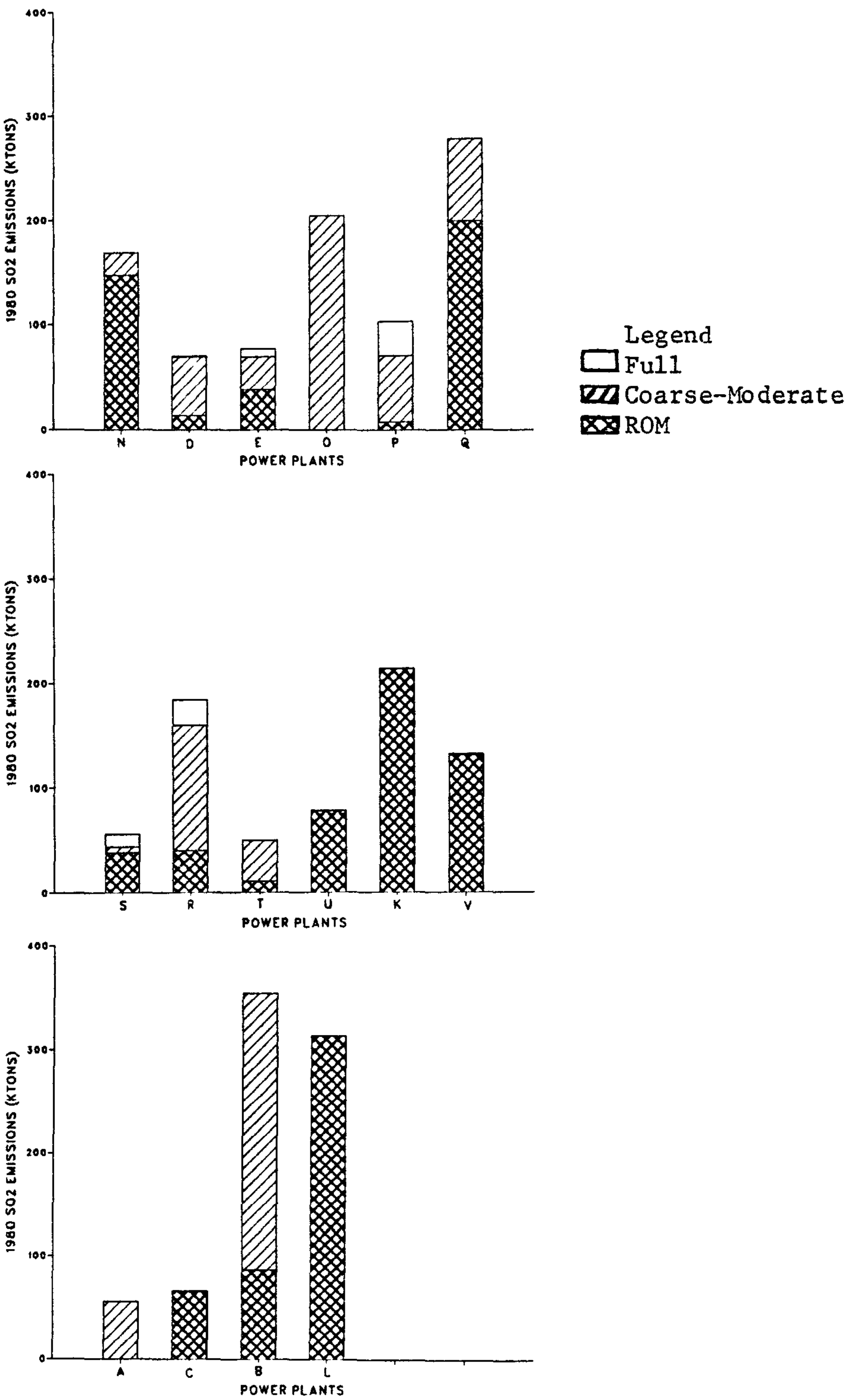


Fig. 9 Power-Plant SO_2 Emissions, 1980 (10^3 ton SO_2/yr)

- Most plants that are not mine-mouth power plants typically have from one to three favored suppliers that account for the bulk of their coal.

- Very few facilities have adopted a strategy of making many small (<10,000 ton) coal purchases.

In the absence of these trends, the number of coal mines and coals that would have to be evaluated for their washability characteristics would escalate significantly. The number of small coal purchases indicated by Fig. 10 appears to be significant. However, as Fig. 11 shows, the total tonnage of coal involved appears to be all but insignificant, with the exception of facilities D and E. Based on these considerations, it would not seem necessary to evaluate any but the large (>10,000 ton) coal purchases.

4.4 EMISSIONS WITH FULL CLEANING

This study's guidelines recognized that the utilities should be free to determine their own optimal supply strategy. Consequently, the estimated emissions for the fully cleaned coal were based on the reductions that could be achieved by a PCC Level 4 plant recovering 80 percent by weight (wt %) of the ROM coal from the power plant's principal supplier. The amount of coal provided by the principal supplier varied from 23-100% of the power plant's feed, but on the average it was 62%. It should be noted that two plants (L,D) failed to properly complete their FERC Form 423s and could not be included in this study. Plant W burns an unusually high-quality coal that showed an increase in sulfur content with washing because of a combination of low pyritic-sulfur content and Btu losses in cleaning. There seems to be no logical reason for considering this coal further in a washing strategy. Lastly, it was not possible to adequately characterize the principal coal feeding plant X.

The emissions rates for 20 utility power plants appear in Fig. 12. The first bar (identified as "1980 Emissions") in each figure indicates the total 1980 emissions from all coal mines and all coal purchases regardless of size. The second bar ("Major Coal ROM") results from considering the single largest supplier mine for each power plant in 1980 and using the anticipated emissions rate for that coal if it were at the mean value for the given seam and county (see Appendix A). The difference between this value and the "1980 Emissions" bar reflects a combination of several factors:

- Averaging properties from all the coal purchases,

- Departures of the ROM coal from the mean value for the seam, and

- Existing application of some level of PCC techniques to the coal.

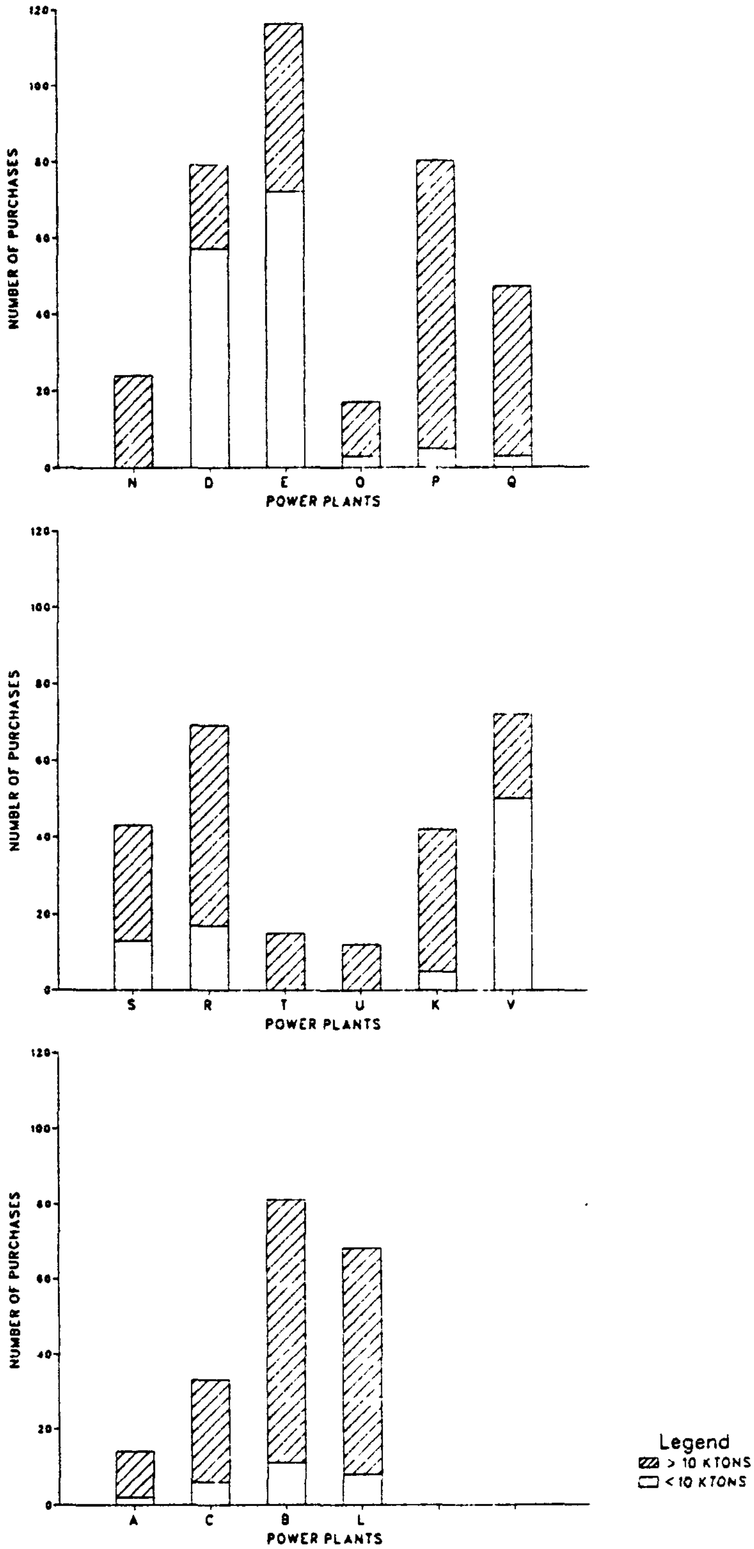


Fig. 10 Number of Power-Plant Coal Purchases

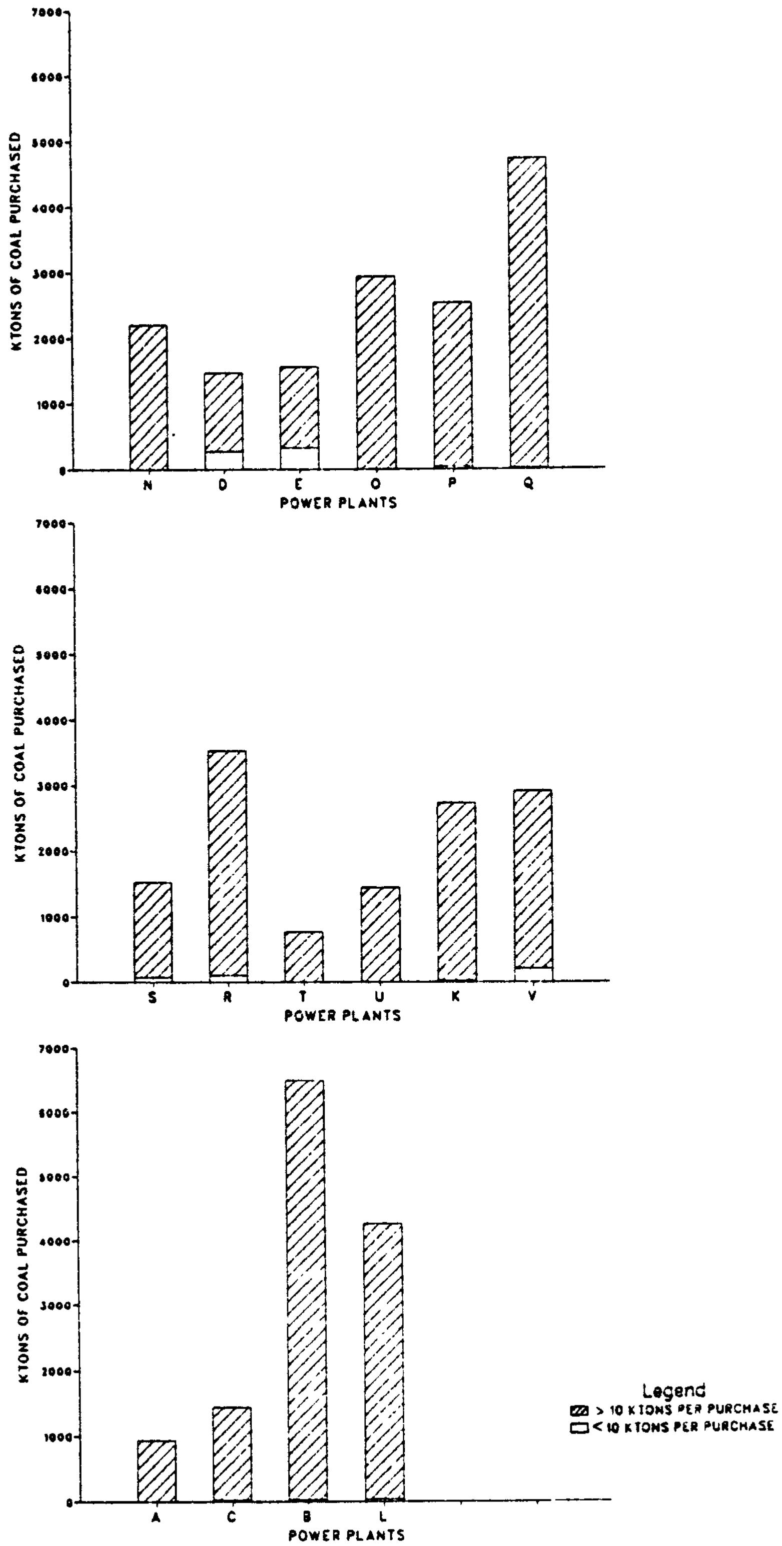


Fig. 11 Coal Tonnages Corresponding to Power Plants' Purchases

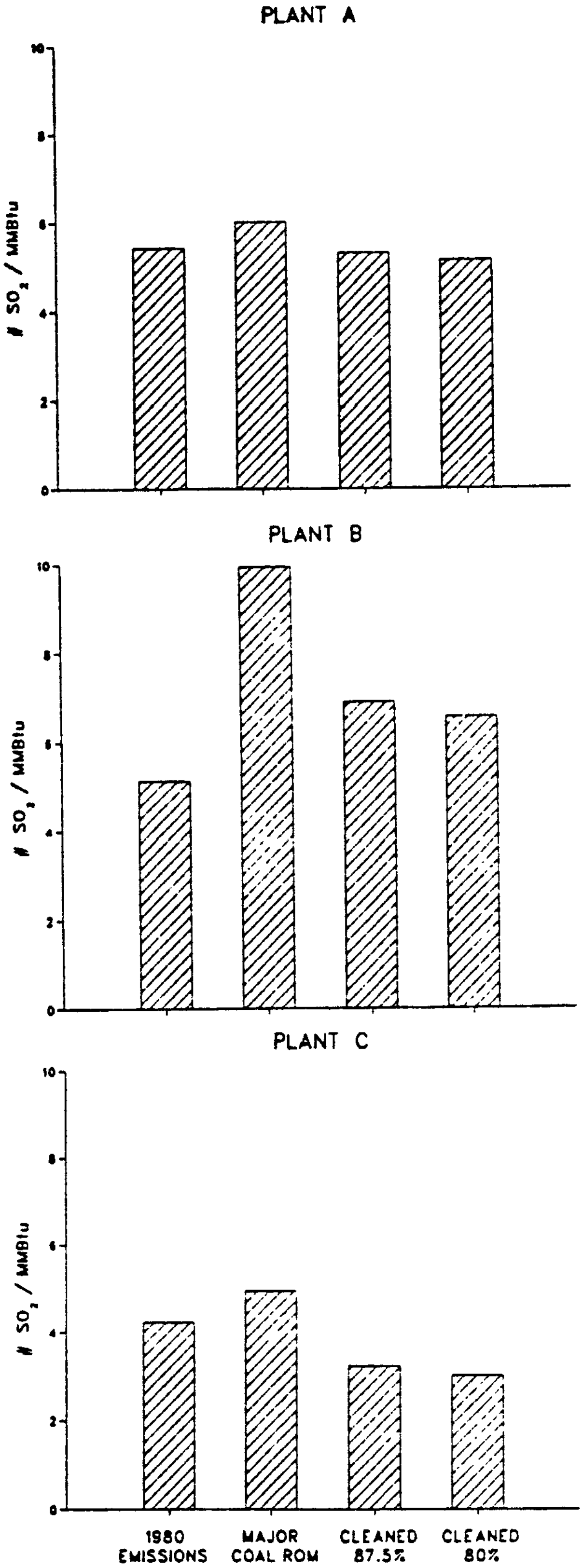


Fig. 12 Sulfur Dioxide Emissions Rates for Selected Utilities

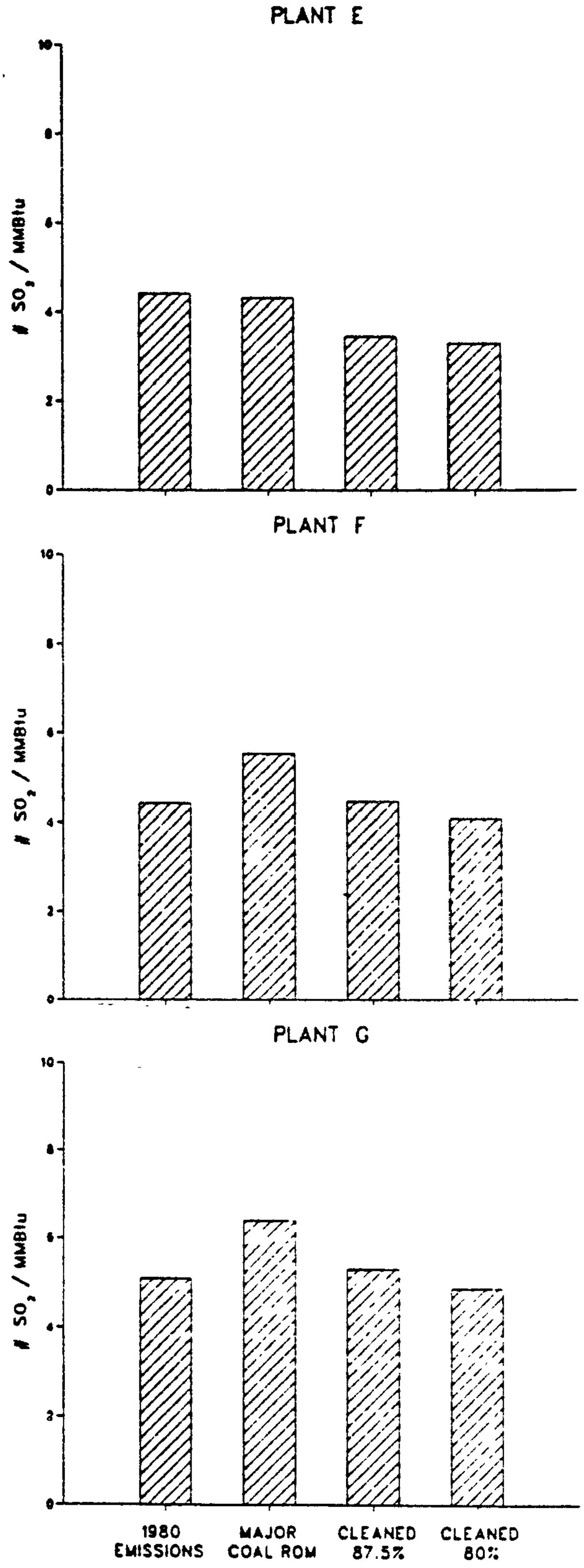


Fig. 12 (Cont'd) Sulfur Dioxide Emissions Rates for Selected Utilities

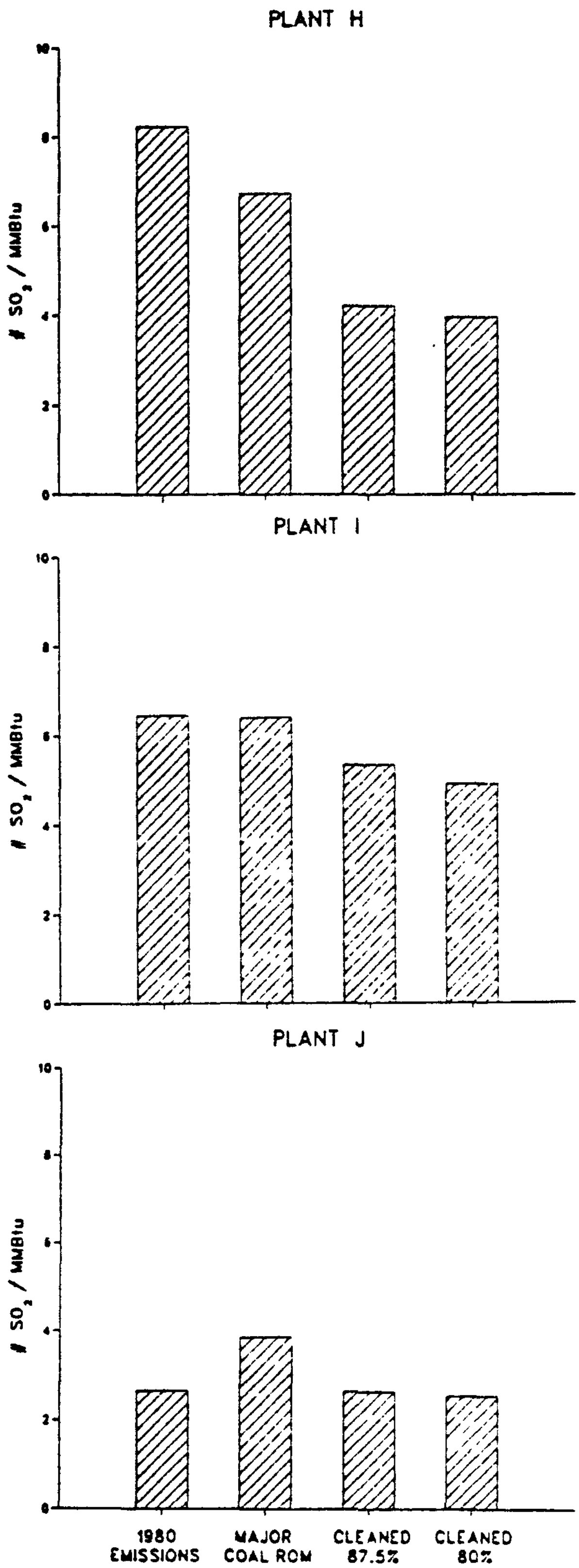


Fig. 12 (Cont'd) Sulfur Dioxide Emissions Rates for Selected Utilities

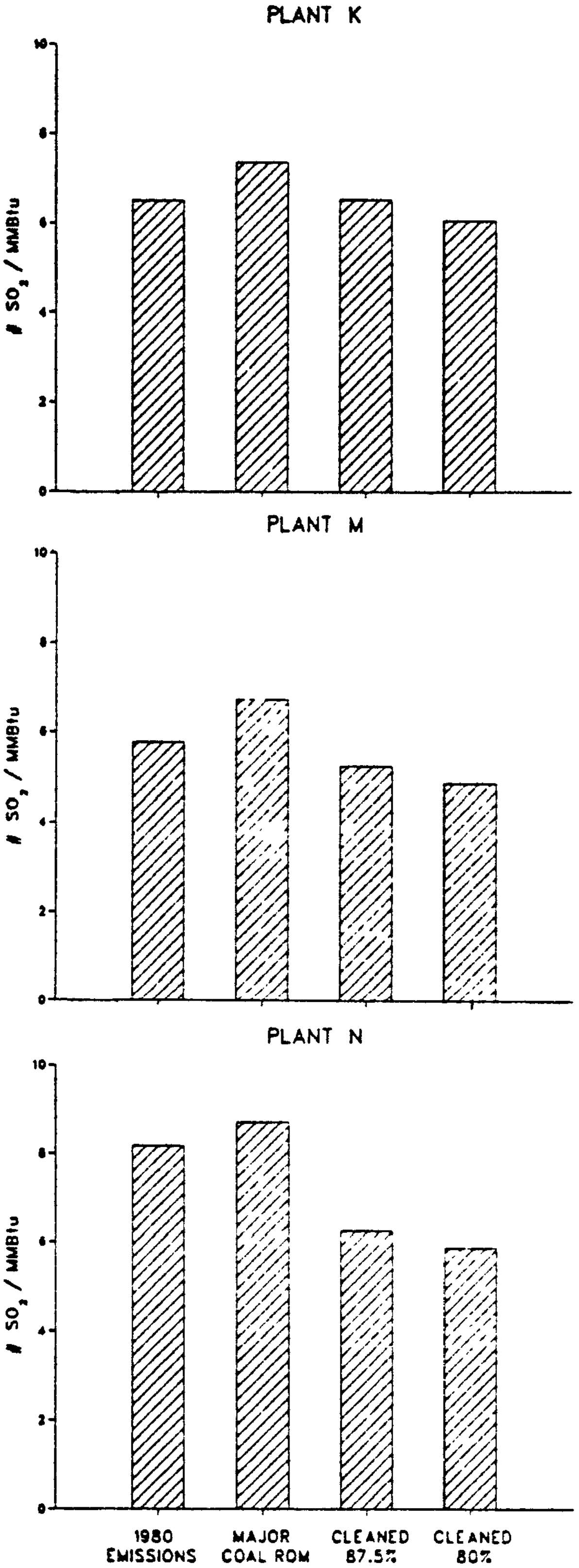


Fig. 12 (Cont'd) Sulfur Dioxide Emissions Rates for Selected Utilities

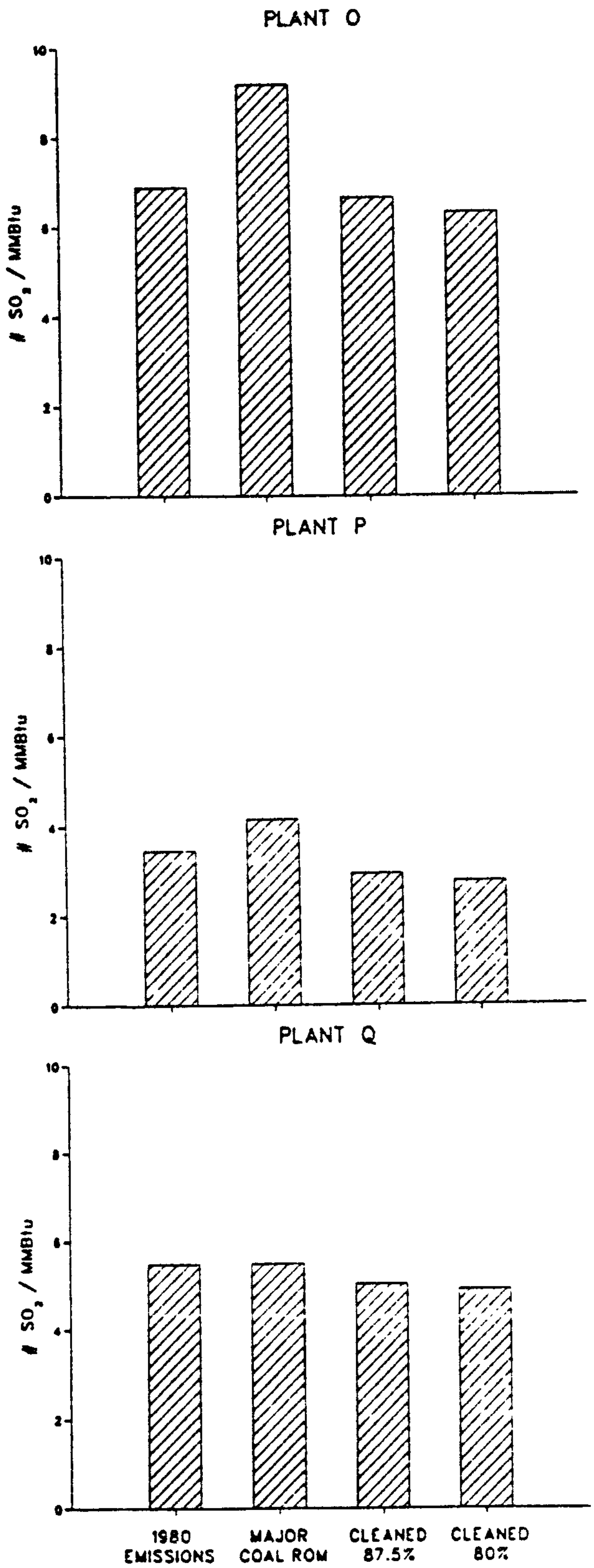


Fig. 12 (Cont'd) Sulfur Dioxide Emissions Rates for Selected Utilities

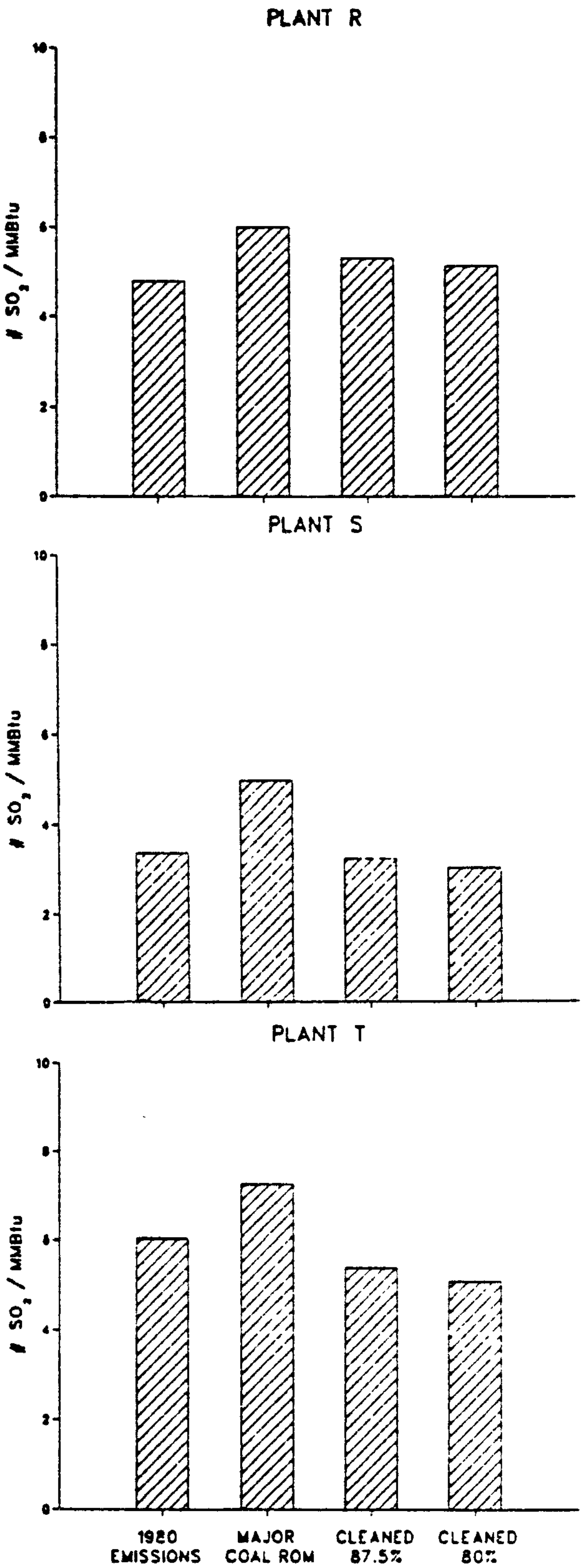


Fig. 12 (Cont'd) Sulfur Dioxide Emissions Rates for Selected Utilities

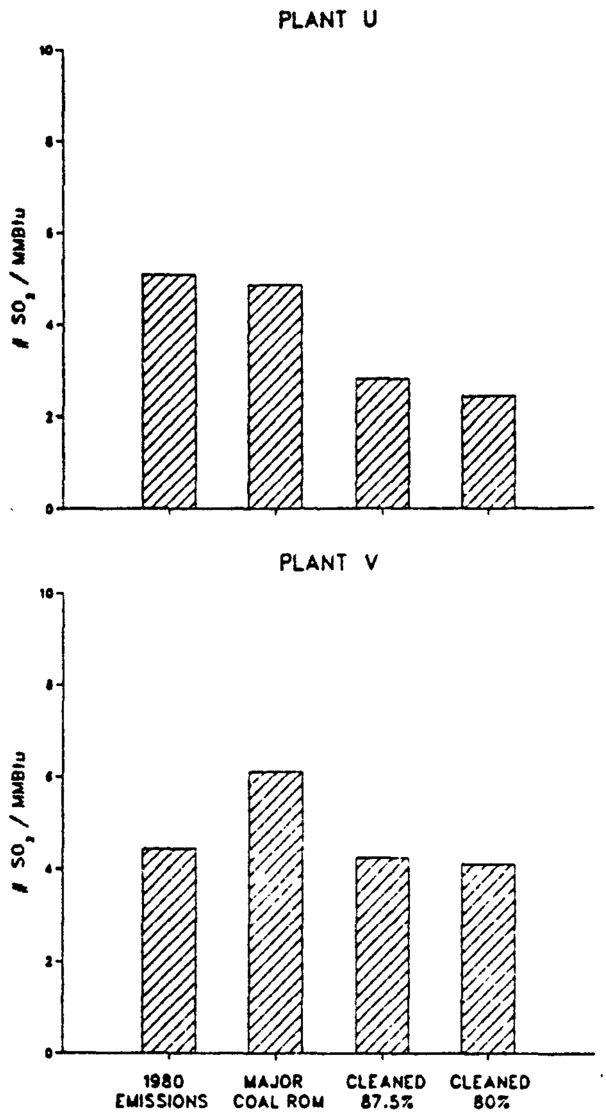


Fig. 12 (Cont'd) Sulfur Dioxide Emissions Rates for Selected Utilities

The first two of these factors could either increase or decrease the difference, while the third factor will almost always decrease the "1980 Emissions" bar.

A computer code that predicts PCC plant washing performance for specific coals was then employed (further discussion of the code is found in Appendix B). The results of this code show that the pyritic sulfur that can be removed by PCC plants when washing to the 80% recovery level will fall in the range of 0-50% of the total sulfur content of the coal, with an average value of 29%.

4.5 COMPARISON OF PCC AND PARTIAL FGD COSTS

The costs of PCC and partial FGD* were compared by calculating system costs on the basis of the dollar cost per ton of SO_2 removed ($/ton SO_2). The coal-cleaning model is described in Appendix B, while the FGD model is based on design studies using the TVA Shawnee code, as summarized in a recent EPRI study.[7] The following assumptions were made in these models:

- Economics were based on November 1982 dollars.[8]

- ROM coal was assumed to have a base selling price at the mine-mouth of $28.15/ton for a 10,678 Btu/lb heating-value coal typical of the Illinois basin.[9] Adjustments made to account for the heating-value variation among the coals considered were calculated at ($2.60/ton)/$10^6$ Btu.

- Two PCC Level 4 plants were considered. One recovered 87.5% by weight of the coal, and the second recovered 80% by weight of the coal.[10]

- The PCC plant was assumed to be available for 3000 h/yr of operation. The remainder of the time could be used for maintenance activity.

- A single conservative shipment rate of $4.64/ton was used for PCC plants that were not mine-mouth operations. This was the mean value from a recent survey of shipment costs for 36 midwestern utilities' coal contracts.[11]

- A constant cleaning cost of $4.74/ton (1978 dollars subsequently adjusted to $6.87/ton in November 1982 dollars) was used for the 80% recovery PCC Level 4 plant.[12]

- The emissions rate for the 80 wt % coal-recovery Level 4 PCC system served as the design base for the FGD system.

- The base FGD system consisted of 500 MW of scrubbed capacity and used four modules of 167 MW-equivalent scrubbing capacity. Three modules are needed in constant operation with a fourth on standby. No adjustments were made for FGD system availability.

*The FGD system would treat only the partial volume of flue gas — 32% on the average — that if scrubbed with 90% efficiency and mixed with unscrubbed gas would yield the same net emissions as are obtained firing cleaned coal.

- Adjustments to the FGD base capacity were made using a power factor of 0.8. No system was permitted to exceed 750 MW or be smaller thn 375 MW.[5]

- The FGD system retrofit increased the base cost by 30%.

- The FGD system was assumed to operate at 90% efficiency. This eliminated reheat requirements by permitting a large fraction of the flue gas to bypass the FGD system.

Details of the resulting cost comparisons based on these assumptions appear in Appendix C. A summary of these data appears in Table 11. The general conclusion to be drawn is that, for 50% of these power plants, PCC is more cost-effective than FGD in meeting the minimal sulfur reductions set forth by the base conditions. A more detailed trade-off study would be needed for another one-quarter of the plants, while PCC appears to be less cost-effective for the remaining plants. Thus, there is not a clear advantage in employing either technology. This is due largely to the wide variations in coal cleanability and the limitations (relative to FGD) on sulfur removal attainable through existing PCC technology. Consideration of other factors, such as effects on power-system availability, waste-disposal concerns, and overall level of SO_2 reductions needed, is necessary before a control strategy can be formulated. In addition to these technical factors, regulatory and institutional concerns can be expected to play an important role. These concerns are discussed in Chapter 5.

4.6 STATEWIDE SULFUR REDUCTIONS

The total SO_2 emissions with and without coal cleaning are shown in Fig. 13 for Ohio, Indiana, and Illinois. Within a 95% confidence limit, there do not appear to be any statistically significant state-by-state variations with respect to total sulfur reduction (at 80 wt % recovery), PCC costs, or FGD costs.

The figure clearly shows that power plant SO_2 emissions in each state are lower than those that would result if only the principal coal were burned with its ROM sulfur content. Note that in Indiana the total emissions are heavily influenced by two plants that already purchase cleaned coal. Consequently, the Indiana 1980 emissions closely resemble those for cleaning at 80 wt % recovery.

In addition to cleaning, many plants buy coal from multiple sources. Much of the coal purchased to supplement the principal coals is lower in sulfur content, thereby reducing the annual totals still more on a statewide basis. However, those coals were not subjected to coal cleaning in this study and hence should not be directly compared against the cleaning results.

Table 11 Summary of PCC Sulfur Reductions, PCC Costs, and FGD Costs

Plant[a]	PCC Level 4, 80 wt % % S Reduction	PCC Level 4, 80 wt % $/Ton SO_2	FGD[b] ($/Ton SO_2)	Costs: PCC/FGD <80%	Costs: PCC/FGD +20%	Costs: PCC/FGD >120%
A	14.57	1366	525			X
B	34.12	354	741	X		
C	39.20	616	1090	X		
E	24.12	1162	978		X	
F	26.16	818	814		X	
G	23.65	778	746		X	
H	41.19	426	979	X		
I	23.65	778	589			X
J	34.08	871	1294	X		
K	17.74	883	593			X
M	27.60	664	754		X	
N	32.56	434	674	X		
O	31.12	435	699	X		
P	33.54	851	1162	X		
Q	10.60	2057	649			X
R	14.57	1366	630			X
S	39.20	616	976	X		
T	29.87	569	598		X	
U	50.03	483	1231	X		
V	32.98	611	854	X		
Average	29.03	809	829	10	5	5

[a]Plants D and L - Omitted because of improper FERC Form 423 reporting.
Plant W - Burns unusually high-quality coal.
Plant X - Inadequate washing data in USGS files.

[b]This FGD system would treat the volume of flue gas that (if scrubbed with 90% efficiency) could be mixed with the unscrubbed gas to yield the same net emission as PCC.

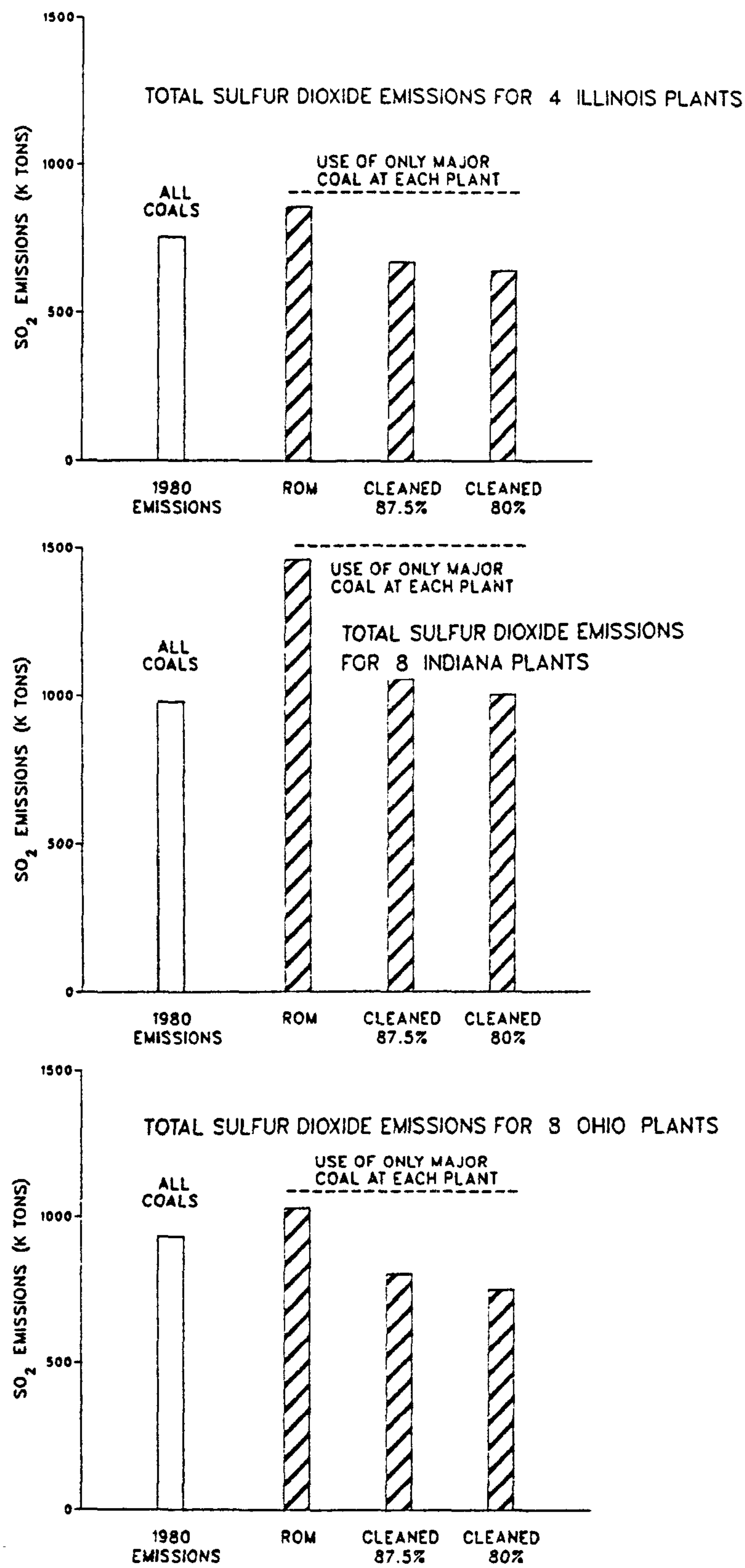


Fig. 13 Total Sulfur Dioxide Emissions for Illinois, Indiana, and Ohio

5 REGULATORY AND INSTITUTIONAL CONSIDERATIONS

5.1 BACKGROUND

Fuel pretreatment was included as a "... technological system for continuous reduction of the pollution generated by a source ..."[13] in the 1977 Amendments to the Clean Air Act. In EPA's promulgation of the utility-boiler new-source performance standards (NSPS) in 1979,[14] physical coal cleaning was determined to be an acceptable method for achieving a portion of the percentage reduction of SO_2 required. Reductions in sulfur content from fuel pretreatment could be credited toward meeting the requirement for greater than 70% reduction. Utilities have not typically considered the addition of coal cleaning as part of a 1979 NSPS-compliance strategy, since the use of an FGD system would be necessary in any case to achieve compliance with the percentage-reduction requirement. Utilities may have decided that the cost and effort needed to gain credit from washing coal was simply not economical.

Portions of the utility industry are supporters of the virtues of coal cleaning. The Electric Power Research Institute (EPRI), for example, not only has funded a coal-cleaning test facility, but has become an active proponent of the advantages of cleaned coal to utilities. EPRI noted[15] that less than 20% of the coal used annually by the utility industry is cleaned, despite the benefits EPRI perceives in cleaning coal — lower shipping costs, improved boiler operation, and reduced sulfur emissions. If cleaned coal is used to augment scrubbers, EPRI argued that the performance of the FGD is improved and some of the operating costs (sludge disposal, limestone) are reduced. American Electric Power (AEP) has also been quoted as "... enthusiastically endorsing coal cleaning."[16] AEP, however, was enthusiastic over the use of cleaned coal for improving the performance of boilers and the availability of power plants, not over the sulfur-reduction potential of cleaning. AEP stated that it would be "... cheaper to buy high-quality cleaned coal to get peak availability from existing plants than to build new plants to replace what is lost to bad coal."[16]

More recently, congressional activity in the area of legislation to control acid rain has focused attention on strategies for SO_2 reduction, including coal washing. Several of the many bills introduced into the 97th Congress (e.g., H.R. 4829, the Moffett Bill) specifically referred to precombustion fuel cleaning as an approach to emission reduction. Congressional debate had indicated an interest in a mandatory coal-washing policy, but no bill specified such pretreatment as a requirement. In most cases, the proposed legislation gave states in the Acid Rain Mitigation (ARM) region — 31 states east of the Mississippi plus Iowa, Missouri, Arkansas and Louisiana — significant flexibility in choosing SO_2 reduction methods. Proposed legislation to control acid rain was introduced into the 98th Congress. Again, coal washing is an optional strategy for SO_2 reduction but not a requirement. Congressional interest in the sulfur removal possible with coal washing may be reviving. For example, the Congressional Research Service has recently initiated a study of coal washing — costs, SO_2 reduction potential, market forces, etc.

5.2 CONSTRAINTS ON VOLUNTARY USE OF CLEANED COAL

There are a number of potential constraints on the widespread voluntary use of coal-cleaning — those that involve possible institutional limits on the expansion of the coal-cleaning industry and those that involve the limits to the acceptability of cleaned coal by the utility industry. Among the most obvious problems facing the coal-cleaning industry are the lack of demand for the product and the major capital-investment requirements for construction of a new cleaning plant. The low demand is a function of the costs of cleaned coal (as noted in Sec. 3.1.9), possibly exacerbated by the current decline in the demand for energy and the postponements and cancellations of proposed new power plants. (For example, in 1977 the Energy Information Administration projected a need for 242 GW of additional coal-fired generating capacity coming on-line between 1980 and 2000. The most recent projection, NEP-3[17] [July 1980] has reduced the additional capacity needs to 181 GW.) The major investors in coal-cleaning facilities are large coal companies and utilities. Investment in a coal-cleaning plant by an independent entrepreneur seems unlikely, unless a market for the product were more assured. In addition, the likely economies of scale place smaller coal producers at a disadvantage, making them unable or unwilling to invest in cleaning facilities.

There are additional constraints on the possible expansion of a coal-cleaning industry that arise from environmental regulations. Coal-preparation plants emit pollutants to air, water, and land in the process of cleaning coal. Consequently, plants face both known regulations (e.g., air-quality NSPS limiting particulate-matter emissions, water-quality limits on toxic effluents) and possible future regulations (e.g., if coal cleaning waste is classified as hazardous under RCRA, significant costs will be associated with safe disposal). Not only is there uncertainty about the environmental regulations with which the cleaning plant must comply, there is uncertainty about the future of regulations for the potential customers of the cleaned coal. The uncertainties in this case range from possible Congressional revisions to the Clean Air Act (e.g., making the Act less stringent by dropping the percentage-reduction requirement or making it more stringent by adding acid-rain controls) to variations in EPA's implementation (e.g., requiring revisions to make state-implementation-plan [SIP] emission limits more stringent in nonattainment areas or allowing SIP revisions to relax emission limits in attainment areas).

Although coal cleaning has long been used for removing ash and improving the Btu content of coal, utilities (or other sources of demand for washed coal) appear to have a generally limited knowledge of developments in cleaning technologies and the uses of cleaned coal as a sulfur reduction technique. A study conducted by Battelle Columbus for EPA included interviews with a number of utility officials and concluded that "existing engineering/economic studies of physical coal cleaning are believed to provide a wholly inadequate basis for investment decision making."[18] Even if a utility executive had adequate knowledge to make an investment decision, the current tax status of the investment might dissuade him. A utility's investment in a coal-cleaning facility does not have the same tax status as an investment in an FGD system. The latter is defined as a pollution-control investment, with such financial advantages as accelerated depreciation and investment tax credit. On the other hand, if independent coal companies were to invest in cleaning facilities, the costs could be added to the fuel costs to the utility and possibly become part of the fuel adjustment clause, passing the costs directly on to the consumer. The pass-through of the costs is not a certainty, however; it would depend on the decision of a public utility commission.

5.3 OPTIONS FOR INCREASING THE USE OF CLEANED COAL

If it is assumed that cleaning coal is a useful method for reducing SO_2 emissions and that it is desirable to encourage the use of cleaned coal in coal-burning facilities, then there are a number of policies that could be initiated by the federal or state government either to encourage or to require the increased use of cleaned coal.

5.3.1 Policies to Encourage the Use of Cleaned Coal

Encouraging an expanded supply of and demand for cleaned coal by providing incentives is difficult and not likely to be effective in the short run. Following is a list of some actions the state or federal government could take to overcome some of the barriers to an expansion of the coal-cleaning industry:

- Provide loan guarantees for the construction of coal-cleaning plants
- Provide tax incentives or direct subsidies
- Clarify the acceptability of the additional costs of cleaned coal for a fuel adjustment
- Undertake a substantial publicity (i.e., public information) program
- Provide price guarantees for the cleaned coal
- Reduce uncertainty in the market by stabilizing SIP regulations.

Other possible actions could be taken at the federal government level:

- Alter the current IRS approach and allow coal-cleaning plants to be treated as pollution-control investments

- Set a time period for a moratorium on changes in NSPS regulations, thus ensuring a more stable market

- Consider incentives to coal cleaning in the proposals for an industrial-boiler NSPS.

The actions listed above all work through encouraging the supply of and demand for cleaned coals, and all assume that the demand for cleaned coal will exist. If this assumption is not valid, the government will find itself locked into a position of permanent subsidization of an industry, which seems unlikely to be a cost-effective approach to reducing SO_2 emissions. In some cases, the actions would require the commitment of an indeterminate amount of public funds to support one industry. Considering the current depressed economy, large federal deficits, and declining state revenues, it seems unlikely that such government action will take place.

The Environmental Protection Agency could review possible actions to encourage coal cleaning, although the EPA has limited statutory authority available for requiring the use of cleaned coal. According to the Clean Air Act Amendments (Sec. 111), the EPA is empowered to set standards of performance for new sources, but not to require any specific control technology. EPA's allowance for crediting fuel pretreatment toward the percentage removal requirement of the 1979 NSPS could be viewed as a policy of encouragement. In addition, the agency could:

- Review and simplify the procedures required for monitoring coal samples and determining SO_2 removal efficiency.

- Set a higher limit on the minimum lot-size subject to sampling (The current NSPS sets a lot size as the weight of coal processed in 24 hours; if more than one coal is treated in a single day, a sample of each type must be collected and analyzed.)[14]

- Encourage the inclusion of a requirement for cleaned coal in an SIP, by preparing control guidelines for reasonably available control technology (RACT) for SO_2, indicating the potential clean-up from washing coal and the acceptability of such an SIP attainment strategy.

5.3.2 Policies to Require the Use of Cleaned Coal

Another set of policies could be undertaken to require the use of cleaned coal. Congressional action as part of acid-rain legislation could establish a mandatory coal-washing policy. The most likely governmental level for action to increase the use of cleaned coal is, however, at the state level. State air-quality-control agencies could make the SIP requirements for existing coal-fired facilities more stringent or require a percentage reduction from a base year of emissions. The justification for such an action would need to be the protection or enhancement of air quality in the state — to bring a nonattainment area into attainment, to protect a PSD increment, to provide a growth allowance for future sources of SO_2 emissions, or to protect sensitive ecosystems. Increasing the stringency of SO_2 regulations would not necessarily lead to an increased use of washed coal, however. Lower-sulfur coal could be purchased and blended. In the midwestern states reviewed in this study, a requirement to use local coal might be necessary to avoid the increased use of out-of-state lower-sulfur coal. A local coal requirement would likely require action by the state legislature.

Depending on the statutory power of a state regulatory agency, a specific requirement for use of washed coal in utilities could be made (action to revise state codes might be necessary in some states). Regulations could be promulgated to:

- Require a percentage reduction of sulfur by washing for all sources. Such a requirement might be technically infeasible for all the coals in a state or might be very inefficient in terms of Btu losses. Therefore, limits need to be set.

- Require the removal of x% of sulfur, if uncontrolled emissions are $> y$ lb $SO_2/10^6$ Btu and if $< z$% loss in Btu occurs. If the coal cannot be washed to x%, or if the raw coal is already low in sulfur content, or if significant losses in terms of Btu content will occur, then the requirement will not be enforced.

- Set an emissions cap for each power plant in the state. An emissions cap would need to be carefully chosen, such that the use of washed coal would be encouraged. This option is a combination of mandatory and incentive approaches.

- Set regulations for each source. The results of this study suggest that a source-specific regulatory strategy would be the most effective choice for The states and utility plants reviewed. This alternative would place heavy demands on the staff of an agency. Moreover, in the absence of a local air-quality problem (such as nonattainment) or of a federal requirement for states to reduce SO_2 emissions (such as proposed in the acid-rain bills in the U.S. Congress), a selective regulatory action could face serious problems of acceptability. Equity issues could be referred to in an initiative that would require one power plant to use washed coal, increasing the costs of its fuel, while another power plant would not be so required.

An effort to implement a mandatory coal-washing policy was undertaken in Ohio, starting with the 1979-80 legislative session.[19] A number of bills were discussed at the committee level, but none were reported out of the committee for consideration by the General Assembly. The bills proposed revising the state code, allowing the director of the state EPA to require coal washing by all the utilities. The director was to issue specific coal ashing standards for each source, giving consideration to "... whether the requirement of such action would be technically infeasible or economically unreasonable and whether the costs of such requirements would be disproportionate to the benefits to be derived therefrom." Initially the Ohio EPA[20] had considered including industrial boilers in the proposed requirement, but instead decided to concentrate on utilities. A number of utilities and small coal producers objected to the proposed bill. The agency has not revived the proposal, since there has been a substantial voluntary increase in the use of washed coal by the utility companies in the state.

6 CONCLUSIONS

6.1 DATA ON POWER PLANTS' COAL USAGE

The selection of power plants for study and determination of their coal supply characteristics was accomplished with the aid of reports and data bases available from the U.S. Federal Energy Regulatory Commission, the Energy Information Agency, and the Bureau of Mines. In most cases, these data were adequate to identify the mines supplying each plant, to establish coal-purchase patterns, and to predict SO_2 emissions corresponding to the delivered coals. Unfortunately, two plants with relatively high SO_2 emissions reported coal-purchase data in such a way that the specific suppliers could not be identified. These plants had to be dropped from consideration in the study. Two other plants were also dropped: one because it fires coal that is not amenable to cleaning, and the other because its source of raw coal could not be adequately characterized. This left 20 plants for evaluation.

The coal-purchase data revealed that:

- Power plants, even mine-mouth facilities, typically buy from several suppliers.
- Most plants have one to three suppliers that account for the bulk of their coal; on the average, 62% of the coal for a given plant comes from a single source.
- Most plants buy coal in lots of 10,000 tons or more.
- Total annual SO_2 emissions (a function of plant size, coal characteristics, and capacity factor) vary over a range of about 6.75 to 1 among plants.

The last fact listed implies that significant emission reductions could be obtained through application of coal cleaning (or other controls) to only a subset of the plants included in this study.

Most of the plants already have SO_2 emissions lower than are predicted from run-of-mine characteristics of the major coal purchases. In some cases, this is due to small purchases of low-sulfur coal for blending. However, analysis of delivered-coal versus raw-coal characteristics indicates that some degree of coal cleaning is being employed by many suppliers (approximately one-third of the coal evaluated in this study). Details of the cleaning processes are not generally available, although data on coal-cleaning equipment installed at specific facilities are reported. We utilized those data, together with the coal characteristics, to infer the cleaning level for each coal. We concluded that very little coal is receiving the extensive cleaning modeled in this study (see Fig. 9), so no attempt was made to develop incremental SO_2 reductions for changing from coarse to full beneficiation.

6.2 EMISSION REDUCTIONS DUE TO COAL CLEANING

The principal coal (i.e., the coal from the single largest supplier) was identified for each power plant and subjected to a washability analysis. The computer model used is based on a typical Level 4 cleaning plant flowsheet, and no optimization was attempted for specific coals. In commercial practice, cleaning plants are generally unique, being designed with particular coals and markets in mind. Thus, some performance improvements over those predicted here may be possible, although it is not feasible to make any quantitative estimates at this time.

A larger uncertainty in the results stems from the observed variations in coal washability, even for coal samples from the same seam and mine. Where possible, we used washability data obtained using coal samples from the particular mine supplying the principal coal. In other cases, the closest possible match was at the county and coal-seam level. More accurate predictions would require extensive sampling and washability analysis of coal yet to be extracted at each mine.

The average sulfur reduction predicted was about 29%, with a standard deviation of 9.9%. The minimum reduction was only 10.6%, while a 50% reduction was predicted for one coal. Differences in the fraction of the sulfur occuring as pyrites and in the size distribution of the pyritic particles account for most of the variation. The degree of reduction also depends somewhat on the weight recovery of coal in the cleaning process (i.e., how much coal the operator is willing to throw out along with the unwanted mineral matter). We investigated both 80% and 87.5% weight recovery and found that the lower recovery improved the sulfur removal by an average of about 22% over the higher value. Our results are thus based on 80% recovery, which is within the range of accepted commercial practice.

6.3 COAL CLEANING VS. PARTIAL FGD

The costs for sulfur dioxide control by PCC (in terms of \$/ton SO_2 removed) were compared with those for limestone-slurry FGD. It was assumed that the FGD systems would be designed to meet, but not improve on, the SO_2 emissions rates set by PCC. This was accomplished by specifying FGD systems sized to treat only a portion — 32% on the average — of the flue gas at an SO_2 removal rate of 90%. When this portion of the gas stream was mixed with the untreated gas, the net effect was the same as for combustion of cleaned coal. A 30% increase in FGD system installed cost was used to account for retrofit difficulty.

The comparison indicated that:

- PCC is more cost-effective than FGD for 50% of the plants,
- PCC and FGD costs are comparable for 25% of the plants,

- FGD is more cost-effective for the remaining 25% of the plants, and

- There are no statistically significant variations (at a 95% confidence level) in percentage sulfur reduction, PCC costs, or FGD costs among the three states included in this study.

Costs (in 1983 dollars) for PCC ranged from \$354 to 2057/ton SO_2, with an average of \$809/ton SO_2. For FGD, the range was \$525-1294/ton SO_2, with an average value of \$829/ton SO_2. While these costs are indicative of the values and variations that could be expected, they have not been adjusted for site-specific technical and economic factors that could significantly affect the results in any given case.

Other factors should also be considered in comparing PCC and FGD. Specifically, PCC can:

- Reduce coal-transportation requirements (reduced secondary emissions and public safety hazards),

- Produce a more uniform fuel,

- Improve boiler efficiency by reducing slagging on boiler tubes,

- Reduce load factors for ash-collection and handling systems (as well as any existing FGD systems), and

- Improve overall plant availability.

In contrast, FGD systems can:

- Accommodate coal switching and

- Achieve much higher sulfur reductions than PCC.

Furthermore, PCC plants can be (and generally are) constructed at a mine or central location independent of any particular consumer. Assuming that there is a sufficient market for the cleaned coal, this removes the economic constraint encountered in retrofitting new control equipment (e.g., FGD systems) on older plants.

6.4 REGULATORY AND INSTITUTIONAL CONSIDERATIONS

The existing use of coal cleaning is fairly widespread, but it is not directed primarily at sulfur reduction. Voluntary application of "deep" cleaning techniques such as those modeled in this study is likely to be constrained by a number of factors, including:

- A less favorable tax status for PCC plants as contrasted to FGD systems,
- Lack of an assured, stable market for the coal,
- Major capital investment requirements,
- Economic disadvantages (scale factors) for small producers,
- Uncertainties regarding future environmental legislation and impacts of existing regulations under the RCRA, and
- A perceived lack of adequate data for investment decision-making.

A number of possible measures to encourage the voluntary use of cleaned coal were suggested in Sec. 5.3.1. These included such actions as loan and price guarantees, changes in the tax laws, and stabilization of regulations for a guaranteed period of time. None of these measures is likely to have much effect in the short term, and those requiring commitment of government funds would almost certainly be difficult to legislate.

Requirements for coal cleaning have been proposed at the federal level as part of acid-rain legislation. While these are still under consideration, the most likely governmental level for implementing a cleaning requirement is the state level. State Implementation Plans could be revised to:

- Require a percentage SO_2 reduction for all sources,
- Set an emissions cap for each power plant,
- Require a percentage removal of sulfur if uncontrolled emissions are greater than a threshold value, or
- Regulate SO_2 levels for each source individually.

Application of any of these measures could promote the use of cleaned coal. However, the regulations would have to be flexible and applied with care to avoid driving certain coals (and coal producers) from the marketplace because of poor cleanability. Furthermore, actions involving emissions caps could stimulate the transportation of low-sulfur coals unless requirements for "local" coal use were also enacted. Experience in Ohio has indicated that it is quite difficult to put together an acceptable legislative/regulatory package.

In conclusion, coal cleaning has the potential for significant sulfur reductions when applied to many of the coals now being used in the study region. The technology should be considered in formulating any SO_2 control strategy, but problems arising from coal variability, limited efficacy as compared to FGD, and multiplicity of coal suppliers make a universal cleaning requirement difficult to design and implement.

REFERENCES

1. Nielson, G., Ed., *1981 - Keystone Coal Industry Manual*, McGraw Hill, New York (1981).

2. Jones, R., and M. Jones, *The Effect of Coal Cleaning on the Quantity of Sulfur Dioxide and Ash Produced by Coal-Fired Power Generation in the Northeastern United States*, U.S. Department of Energy Report, DOE/ET/12512-2 (May 15, 1982).

3. Argonne National Laboratory and Bechtel Corporation, *Environmental Control Implications of Generating Electric Power from Coal*, Argonne National Laboratory Report, ANL/ECT-3, Appendix A, Part 2 (Dec. 1977).

4. *Environmental Control Implications of Generating Electric Power from Coal*, prepared by Bechtel Corp. for Argonne National Laboratory, ANL/ECT-3, Appendix A, Part 1 (Dec. 1977).

5. Doctor, R., *Utility Flue Gas Desulfurization: Innovations and System Availability*, Argonne National Laboratory Report, ANL/ECT-11 (March 1982).

6. Laeske, B., *Trends in Commercial Application of FGD Technology*, EPA/EPRI, 7th Symp. on Flue-Gas Desulfurization, Hollywood, Fla. (May 17-20, 1982).

7. Dunlop, W., *Economic and Design Factors for Flue Gas Desulfurization Technology*, Electric Power Research Institute Report, EPRI CS-1428 (April 1980).

8. *Economic Indicators*, Chemical Engineering *90*(1) (Jan. 10, 1983).

9. *Coal Outlook*, Pasha Publications, Washington, D.C., *6*(46) (Nov. 29, 1982).

10. Phillips, P.J., et al., *Coal Preparation for Combustion and Conversion*, Electric Power Research Institute Report, EPRI AF-971 (May 1978).

11. *Coal Outlook Supplement*, Pasha Publications, Washington, D.C., *6*(40) (Oct. 18, 1982).

12. Burhoff, J., et al., *Technology Assessment Report for Industrial Boiler Applications: Coal Cleaning and Low Sulfur Coal*, U.S. Environmental Protection Agency Report, 600/7-79-178c, p. 338 (Dec. 1979).

13. 42USC 1857 et seq., Sec. 111(a)(1).

14. 44 FR33580 - 33624, NSPS: *Electric Utility Steam Generating Units* (June 11, 1979).

15. Lihach, N., *More Coal Per Ton*, Electric Power Research Institute Journal, pp. 6-13 (Jan. 1981).

16. Blackmore, G., *Coal Preparation Improves Utility Efficiencies*, Coal Age, pp. 70-77 (Jan. 1981).

17. DOE/Office of Policy, Planning, and Analysis, *Energy Projection to the Year 2000*, U.S. Department of Energy Report, DOE/PE-0029 (July 1980).

18. *Use of Coal Cleaning for Compliance with SO_2 Emission Regulations*, prepared by Battelle Columbus Laboratories, for U.S. EPA/IERL, PB81-247520 (Sept. 1981).

19. Bill to Enact Sec. 3704.17 of the Revised Code, 113th General Assembly, Regular Session (1979-1980).

20. Private Communication with Staff of Ohio Environmental Protection Agency (March 2, 1983).

APPENDIX A

COAL DATA BASE

As a result of work performed at Argonne National Laboratory using the large analytic and reserve coal data files from the United States Bureau of Mines (USBM), it was decided to facilitate future coal studies by organizing these data in a manner that would allow for quicker and easier retrievals by computer. Therefore, the complete USBM analytic and reserve data files (6.9 megabytes of data) were stored in 1978 in an interactive data base (this provides for data current as of 1976).

In a related effort,[3] coal-washability and coal-reserves data were integrated to match reserves and washability whenever possible. Two computer programs were developed to match the appropriate entries in each data set and then merge the data into the form presented in the report. Approximately 18% of the total demonstrated coal reserves were matched with washability data. Moreover, about 35% of the reserves that account for 80% of current production were successfully matched. Each set of merged data specifies the location and size of the reserve, selected physical and chemical characteristics of the coal, and washability data at three crush sizes (1.5 in., 3/8 in., and 14 mesh) and several specific gravities. In each case, the percent recovery, Btu/lb, percent ash, percent sulfur, and lb $SO_2/10^6$ Btu are given. These data, combined with the mine-specific information that appears in Tables A.1-A.5, served as the basis for this report. The tables include data for 53 mines that were principal suppliers to those plants in Illinois and Indiana (with a few in Ohio) that are part of the FERC midwestern distribution grid. The mine identifications were obtained from the FERC regional office in Chicago, with supplementary information from Ref. 1.

Table A.1 Available Preparation Equipment for Coal Mines in Illinois

						Available Preparation Equipment														
Plant Number	Location of Mine: County (Nearest City)	Seam	Mine	Company	Level of Cleaning	Magnets	Breaker	Crusher	Dryer	Screens	Washing Tables	Air Tables	Cyclone	Centrifuge	Flotation	Jigs	Heavy Media	Thickener	Filter	Other
1	Wabash (Keensburg)	#5	Wabash	Amax Coal Co.	2-3	X		X		X										
2	Montgomery (Coffeen)	#6	Hillsboro	Consolidated Coal Co.	1															
3	Jefferson (Waltonville)	#6	Orient #3	Freeman United Coal Co.	2-3	X		X	X	X					X	X	X			
4	Williamson (Marion)	#6	Orient #4	Freeman United Coal Co.	2-3			X	X					X		X	X			
5	Macoupin (Carlinsville)	#6	Monterey #1	Monterey Coal Co.	2-3	X	X	X		X			X	X		X		X		
6	Macoupin (Albers)	#6	Monterey #2	Monterey Coal Co.	2-3	X	X	X		X			X	X		X		X		
7	Christian (Pawnee)	#6	Mine #10	Peabody Coal Co.	2-3		X	X		X						X				
8	Randolph (Marissa)	#6	Baldwin #1	Peabody Coal Co.	1															
9	St. Clair (Marissa)	#6	River King #6	Peabody Coal Co.	1															
10	Saline (Harrisburg)	#5,#6	Central Preparation Plant	Sahara Coal Co.	4-5	X		X	X	X			X	X			X		X	
11	Randolph (Percy)	#5,#6	Captain	Southwestern Illinois Coal Co.	2-3															
12	Randolph (Percy)	#6	Streamline	Southwestern Illinois Coal Co.	2-3			X	X	X			X				X			
13	Douglas (Murdock)	#6	No. 5 Mine	Ziegler Coal Co.	1		X			X										
14	Williamson (?)	?	No. 4 Mine	Zieglег Coal Co.	2-3															
15	Macoupin (?)	?	Carter	?	2-3															

Table A.2 Available Preparation Equipment for Coal Mines in Indiana

Plant Number	Location of Mine: County (Nearest City)	Seam	Mine	Company	Level of Cleaning	Magnets	Breaker	Crusher	Dryer	Screens	Washing Tables	Air Tables	Cyclone	Centrifuge	Flotation	Jigs	Heavy Media	Thickener	Filter	Other
1	Pike (Selvin)	?	Abbott	Abbott Coal and Energy Co.	1															
2	Clay (Brazil)	III	Chinook	Amax Coal Co.	1		X	X	X	X			X	X		X				
3	Sulivan (Sulivan)	VI,VII	Minnehaha	Amax Coal Co.	1			X		X			X	X		X				
4	Warwick (Chandler	VI	Ayrshire	Amax Coal Co.	2-3		X	X	X	X			X	X	X	X				
5	Knox (Evans-ville)	?	Bicknell Pit #1	Bicknell Minerals Co.	1															
6	Knox (Evans-ville)	?	Apraw	Black Beauty Coal Co., Inc.	4-5															
7	Vermillion	?	Lee	Cambridge	1															
8	Pike (Velpen)	?[a]	Velpen	Hopf Mining Co.	1															
9	Warwick (Warwick)	VI,VII	Tell City	Ohio Valley Coal	1															
10	Pike (Oak-land City)	V	Old Ben #1	Old Ben Coal Co.	1															
11	Pike (Oak-land City)	V[b]	Old Ben #2	Old Ben Coal Co.	4-5															
12	Greene (Carlisle)	VI	Hawthorne	Peabody Coal Co.	2-3			X					X			X				
13	Greene (Dugger)	?	Sycamore	Peabody Coal Co.	1															
14	Vermillion (Universal)	VI	Universal	Peabody Coal Co.	1		X	X					X			X				
15	Warwick (Lyneville)	V	Lyneville 1 & 2	Peabody Coal Co.	2-3		X	X	X				X	X		X				
16	Vigo (Terre Haute)	?	Pit #1	S&G Excavating	1															
17	Pike	-	Enos	Closed	1															
18	Pike	-	Mariah Hill	Closed	4-5															
19	Dubois (in eastern KY and W. Va.)	-	-	D&L Coal Co.	1															

[a]Five seams mined in county

[b]Lower Millenburg

Table A.3 Available Preparation Equipment for Coal Mines in Kentucky

Plant Number	Location of Mine: County (Nearest City)	Seam	Mine	Company	Level of Cleaning	Available Preparation Equipment														
						Magnets	Breaker	Crusher	Dryer	Screens	Washing Tables	Air Tables	Cyclone	Centrifuge	Flotation	Jigs	Heavy Media	Thickener	Filter	Other
1	Muhlenberg (Central City)	?	Gibralter	Peabody Coal Co.	1															
2	Muhlenberg (Green-ville)	#9	River Queen	Peabody Coal Co.	2-3		X	X					X			X				
3	Ohio (Center-town)	#9	Alston	Peabody Coal Co.	1															
4	Ohio (Beaver Dam)	#9,11,13	Homestead	Peabody Coal Co.	1			X												
5	Ohio (Beaver Dam)	#9	Ken	Peabody Coal Co.	4-5			X	X	X	X		X			X				
6	Hopkins (Madison-ville)	#6	Donbow	Tower Resources Inc.	4-5															
7	Ohio (?)	?	ElmGrove	Closed	1															

Table A.4 Available Preparation Equipment for Coal Mines in Ohio

Plant Number	Location of Mine: County (Nearest City)	Seam	Mine	Company	Level of Cleaning	Available Preparation Equipment: Magnets	Breaker	Crusher	Dryer	Screens	Washing Tables	Air Tables	Cyclone	Centrifuge	Flotation	Jigs	Heavy Media	Thickener	Filter	Other
1	Jefferson (Bloomingdale)	Pittsburgh	Betsy	Bolch Mining Co.	2-3					X		X								
2	Columbiana (?)	?	?	C&W Mining Co.	1															
3	Harrison (Cadiz)	Pittsburgh #8	Georgetown #24	Consolidation Coal Co.	1															
4	Belmont (Alledonia)	Pittsburgh #8	Powhatan #1, #3	North American Coal Corp.	2-3		X	X		X							X			
5	Vinton (Chesire)	Lower Mercer, Brookville, Lower Kittanning	Jaymar	Quality Coal Co.	1															
6	Jefferson (Steubenville)	Harlem	Ann #2	W.B. Coal Co.	1															
7	Harrison (Hopedale)	Lower Freeport	Nelms #2	Youghiogheny & Ohio Coal Co.	2-3	X		X		X				X		X				
8	Belmont (?)	?	Ohio Washed	?	2-3															
9	Tuscawaras (?)	?	Blue Creek	?	1															

Table A.5 Available Preparation Equipment for Coal Mines in Pennsylvania

Plant Number	Location of Mine: County (Nearest City)	Seam	Mine	Company	Level of Cleaning	Available Preparation Equipment: Magnets	Breaker	Crusher	Dryer	Screens	Washing Tables	Air Tables	Cyclone	Centrifuge	Flotation	Jigs	Heavy Media	Thickener	Filter	Other
1	Greene (Greensburg)	Waynesburg	Boyle	Boyle Land & Fuel Co.	1															
2	Allegheny (Imperial)	Pittsburgh	Champion 1	Consolidation Coal	2				X		X					X				
3	Greene (Dilliner)	Sewickley	Dunkard	Dunkard Mining Co.	1															

APPENDIX B

COMPUTER MODEL OF COAL PREPARATION

B.1 INTRODUCTION

Computer models for several levels of physical coal cleaning were developed for Argonne National Laboratory by the Center for Energy and Environmental Studies of Carnegie-Mellon University (Contract No. 31-109-38-5236). The authors of the September 1979 study were C.N. Bloyd, J.C. Molburg, D.R. Lincoln, and E.S. Rubin. This study surveyed four preparation levels, from a simple crushing and sizing operation through complete heavy-media washing (including intermediate-size coal and fines).

The essential parameter of coal preparation is overall plant yield, the ratio of mass output to mass input of moisture-free coal. The Btu recovery of the coal based on this parameter and the related production of hundreds of thousands of tons of refuse annually for an average-size coal-cleaning plant is the controlling parameter in the model. What follows is a description of the computer model for the coal-preparation plant as found in the draft report.

3 COMPUTER MODELS OF COAL PREPARATION

3.1 INTRODUCTION

With respect to both economic and environmental consequences, the essential operating parameter of coal preparation is overall plant yield.* Since raw coal feed cost is the largest component of total product cost, the amount of material discarded, as indicated by overall yield, must significantly impact cost. The most evident environmental impact of coal cleaning is the production of refuse. While reduced yield may be required to improve the characteristics of prepared coal, it is necessarily accompanied by increased refuse production. Therefore, overall yield has been chosen as a principal variable for the models described below.

Using these models, specification of overall yield along with certain coal-specific data is sufficient to estimate prepared coal characteristics and cost for several plant configurations. These configurations have been chosen as representative of coal cleaning practice over the usual range of complexity for steam coal preparation. The simplest, or level one, plant is limited to thermal drying to given specifications. A level two plant washes only coarse coal, mixing the finer coal into the product without preparation. In a level three plant some of the finer coal is washed, but only in a level four plant are all coal sizes washed. These plants are described in more detail following some discussion of coal preparation equipment.

3.2 MODELS OF COAL PREPARATION EQUIPMENT

3.2.1 Rotary Breaker

The rotary breaker product is regarded as run-of-mine feed to our coal preparation processes. The most important characteristics of breaker operation are the size distribution of the product stream and the fraction of material

*Defined here as the ratio of mass output to mass input of moisture-free coal.

sent to refuse. Since the rotary breaking is taken to be part of mine operation, the refuse is of no concern to the cleaning plant. The size distribution, however, is. The rotary breaker model must predict the size distribution of the product. That distribution may vary widely due to operating parameters and coal characteristics. However, empirical evidence over a wide range of coals and sizes suggests that the size distribution satisfies the following relationship (Landers, 1946):

$$F(x) = \exp[-(\frac{x}{x_o})^a] \qquad (3\text{-}1)$$

where F(x) is the total weight fraction of material which will not pass through a screen of opening size x. The constants, a and x_o, are material parameters which characterize the subject coal. The range of a is typically 0.5 to 2.9. The screen opening for which F(x) = 1/e = 0.3679 is x_o. This distribution works well to characterize broken or crushed coal. If F(x) is known for any two values of x, a and x_o, can be determined since log[log(1/F(x))] is linear in log x with slope a.

For example, suppose F(4") = 0.09 and F(1/4") = 0.70. Then the fraction of material which will not pass through 4" and 1/4" sieves is 0.09 and 0.70 respectively, and log [log(1/F(x))] = 0.0194 for x = 4"(log x = 0.6021) and - 0.8099 for x = 1/4" (log x = 0.6021).

$$a = \frac{0.0194 - (-0.8099)}{0.6021 - (-0.6021)} = \frac{0.8293}{1.2042} = 0.689 \qquad (3\text{-}2)$$

Then,

$$x_o = x[-\ell n\ F(x)]^{-1/2} = 0.25[-\ell n\ 0.70]^{-1/0.689} = 1.12" \qquad (3\text{-}3)$$

Therefore, the cumulative size distribution function for this example is

$$F(x) = e^{-(x/1.12)^{0.689}} \qquad (3\text{-}4)$$

The weight fraction of material which falls in an interval from x_1 to x_2 is given by $|F(x_2) - F(x_1)|$.

To verify equation 3-1, published size distribution data for 19 coals were checked via least squares regression analysis for adherence to that equation. The results indicated very close agreement with R^2 from 0.9 to 0.99 and an average R^2 of 0.98 for log log(1/F(x)) vs. log x.

A relationship between topsize (TS) and x_o is expected since the size distribution is naturally linked to the topsize. By regression analysis of x_o for the 19 coals considered above, the following relationship has been obtained

$$x_o = 0.897\ TS^{0.467} \qquad (3\text{-}5)$$

The results of that regression indicate that $\ell n\ x_o$ vs. ℓn TS is linear with $R^2 = 0.898$. Ideally, size distribution data will be available. However, in its absence equation 3-5 may be used to estimate x_o. Note that if one data point other than x_o is available, it may be used along with equation 3-5 to approximate the size distribution function. In the absence of any size data, the parameter, a, may be estimated by

$$a = 0.4 + x_o \qquad (3\text{-}6)$$

This very approximate result was also obtained by examination of the 19 coal sample and simply reflects the fact that F(x) approaches zero as x approaches the topsize.

3.2.2 Crusher

The significant characteristic of crusher operation for our analysis is the product size distribution. The discussion of this topic for rotary breakers applies equally to crushers.

3.2.3 Washers

Since all washers rely on specific gravity differences, a single model is proposed for all types. That model requires two types of data: coal-specific washability functions and equipment-specific distribution functions. The weight washability function, $w(i_x, i_{sg})$, predicts the mass fraction of coal in a given size interval, i_x, with specific gravity in the interval i_{sg}. For example, if 15% of 1/4" to 3/8" coal particles have a specific gravity from 1.3 to 1.4, then

$$W(1/4''\text{-}3/8'', 1.3\text{-}1.4) = 0.15 \quad (3\text{-}7)$$

This washability data is required for all washed sizes.

If the size fraction from the previous example were washed at a specific gravity of 1.4 the expected mass yield of clean coal would be 0.15. However, equipment and operating limitations prevent all of the float from entering the clean coal stream. The distribution curve for a specific washer indicates the fraction of coal with a given specific gravity that enters the clean coal stream. This curve will vary according to the washer design, method of operation, and coal particle size. A typical distribution curve is shown in Figure 3.1. Suppose, in the example just described, that the fraction of coal with specific gravity 1.35 (the midpoint of interval i_{sg}) which reports to the clean coal stream is 0.75. Then the contribution to clean coal of particles in the size range i_x is $(0.75)(0.15)\dot{m}_o = 0.113\ \dot{m}_o$, where $\dot{m}_o$ is the total mass flow rate of feed. Similarly, the total mass flow rate in the clean coal stream is:

$$\dot{m}_c = \sum_{i_x} \sum_{i_{sg}} W(i_x, i_{sg}) \cdot D(i_x, i_{sg})\ \dot{m}_o \quad (3\text{-}8)$$

where $D(i_x, i_{sg})$ is the fraction of material in size interval i_x and specific gravity interval i_{sg} reporting to clean coal. The midpoint of the specific gravity interval may be used to locate the appropriate position on the abscissa of the distribution curve.

Simplification of this result is possible through the use of cumulative weight washability functions, which may be designated by $W(TS, i_{sg})$. This

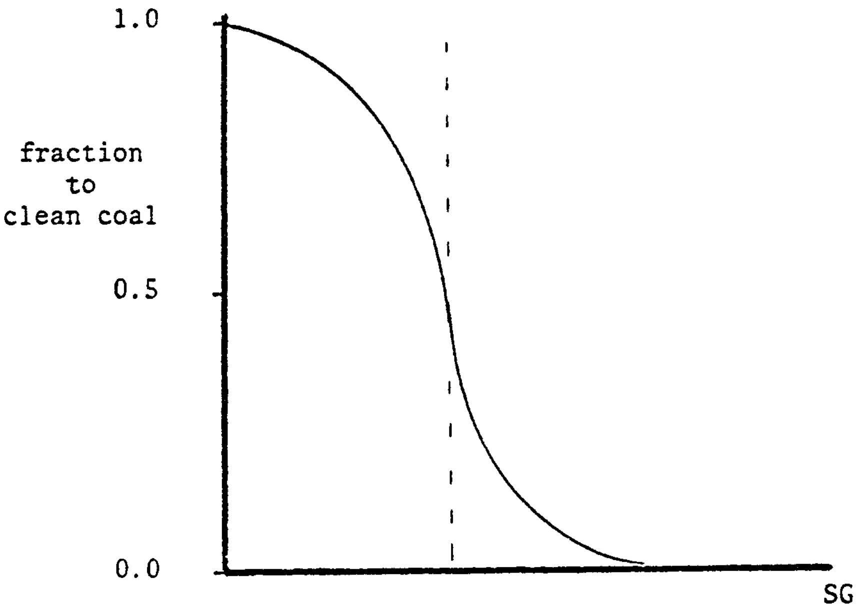


Figure 3.1 Distribution Function

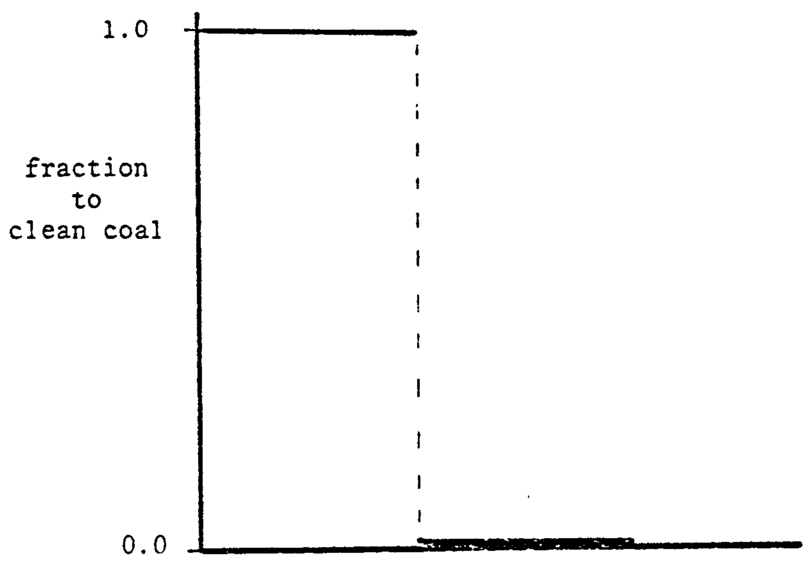


Figure 3.2 Ideal Distribution Function

function indicates the fraction of coal with topsize TS which has a specific gravity in range i_{sg}. If $W(6'', i_{sg}) = 0.37$, then the fraction of coal which will pass through a 6" screen and which has specific gravity in the range designated by i_{sg} is 0.37. A cumulative distribution function may be similarly defined. $D(TS, i_{sg})$ is the fraction of coal of topsize TS and in specific gravity range i_{sg} which enters the clean coal stream. With these functions,

$$\dot{m}_c = \sum_{i_{sg}} W(TS, i_{sg}) \cdot D(TS, i_{sg}) \cdot \dot{m}_o \qquad (3\text{-}9)$$

It is important to note here that $\dot{m}_o$ is the mass flow rate of all material which will pass through a screen of opening TS. A typical washer is used only for a range of sizes from, say, TS to a bottom size, BS. Equation 3-9 can be used for this situation through the use of the previously described size distribution function. The fraction of coal in the range BS to TS is F(BS), where F(x) is based on the topsize, TS. The fraction of material in this size interval and specific gravity interval i_{sg} can be designated $W(TS\text{-}BS, i_{sg})$. A mass balance on the material in this specific gravity range yields:

$$W(TS\text{-}BS, i_{sg}) \cdot F(BS) = W(TS, i_{sg}) - W(BS, i_{sg}) \cdot [1-F(BS)] \qquad (3\text{-}10)$$

Therefore,

$$W(TS\text{-}BS, i_{sg}) = \frac{W(TS, i_{sg}) - W(BS, i_{sg})\,[1-F(BS)]}{F(BS)} \qquad (3\text{-}11)$$

A combination distribution function for a size range TS to BS can also be defined, but the algebra used above does not necessarily apply. This results since the cumulative distribution function represents data from measurements on actual equipment in operation. If that equipment is processing material, from BS to TS in size, only the effect on those sizes will be reported. Cumulative washability data, on the other hand, results from tests of all size particles up to the specified topsize. It is possible to define a cumulative washabiltiy function which applies to a size range BS to TS, thus obviating Equation 3-11. However, much less data is required to use the suggested formulation for various size ranges, than would be required if each range used separate washability data.

Equation 3-8 is consistent with current coal cleaning models used in the detailed design of cleaning plants where accurate estimates of each flow stream volume and characteristics are essential. Where somewhat less accuracy is acceptable the data collection and calculations can be simplified by assuming a special distribution function which is depicted in Figure 3.2. For this distribution, any material with specific gravity below $\hat{SG}$, the specific gravity of separation at which the washer operates, reports to clean coal. The remainder reports to refuse. This means that no material is misclassified according to the specific gravity criteria which is the basis of washer operation.

To qualitatively assess the effect of this approximation on model accuracy consider Figure 3.3 where the fraction of misclassified material of each specific gravity is plotted vs. specific gravity. Note that very little heavy material is substituted for light material except near $\hat{SG}$ where those materials differ only slightly in specific gravity (and hence in properties). The effect of ignoring the misclassification is, therefore, expected to be slight.

$$D(TS, i_{sg}) = \begin{cases} 1.0 \text{ for } SG \leq \hat{SG} \\ 0.0 \text{ for } SG > \hat{SG} \end{cases}$$

Substituting into Equation 3.8

$$\dot{m}_c = \dot{m}_o \sum_{i_{sg}:\, SG \leq \hat{SG}} W(TS, i_{sg}) \qquad (3\text{-}12)$$

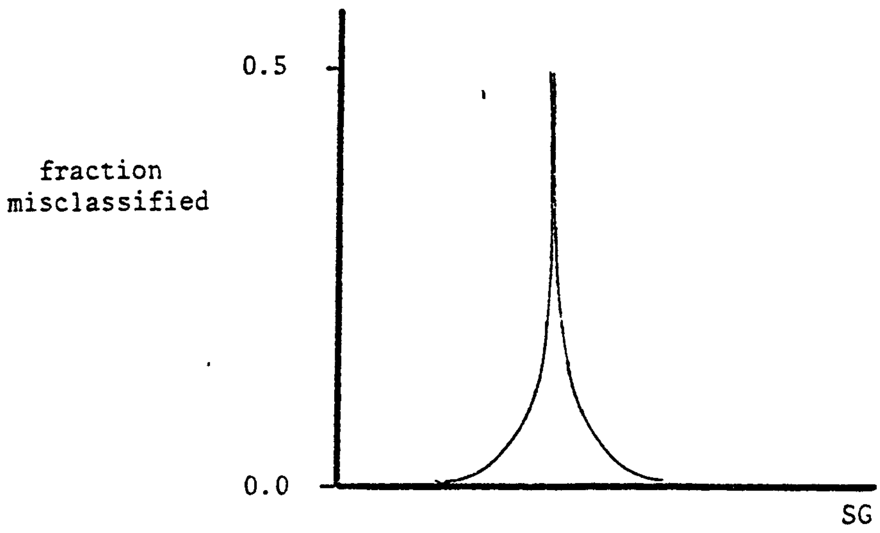


Figure 3.3 Misclassified Material for a Typical Distribution Function.

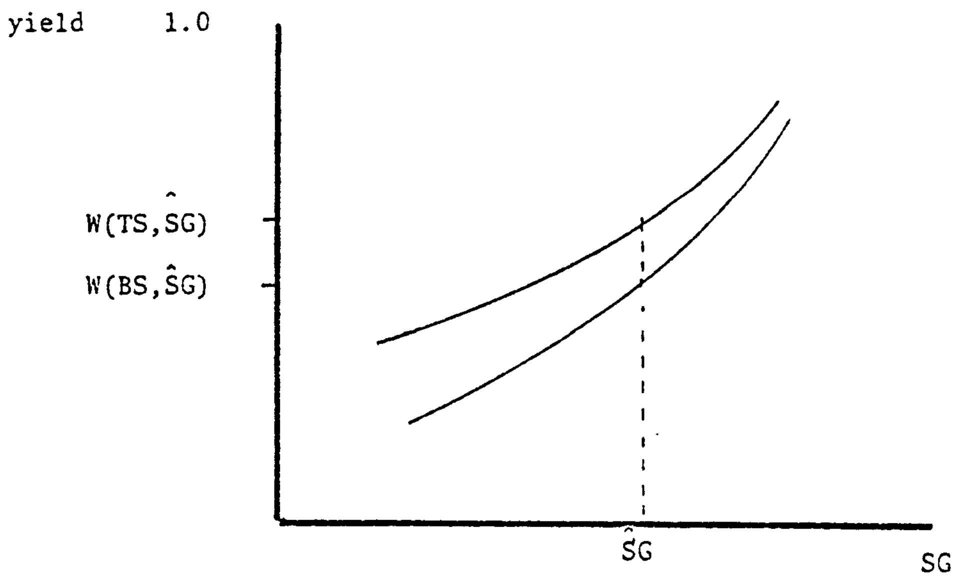


Figure 3.4 Weight Washability Functions

The sum in equation 3.12 has special significance. It is a weight washability function which is cumulative in size and specific gravity. Its value is the total fraction of feed material with specific gravity not exceeding $\hat{SG}$ which will pass through a screen of opening TS. This is washability data of the sort prepared by the Bureau of Mines (Bu Mines RI-8118, 1976). In summary, the cummulative washability data provides an adequate estimate of washer yield for a specified topsize and specific gravity of separation. Note that equation 3-11 still applies.

Accepting an ideal distribution function the weight washability function from equation 3-11 is simply washer yield. Total plant yield is determined by the yields of each washed stream. That is, the yield for any washer is

$$Y = \{W(TS,\hat{SG})[1-F(TS)] - W(BS,\hat{SG})[1-F(BS)]\}\frac{1}{F(BS)-F(TS)} \quad (3.13)$$

where TS and BS are the washer- specific top and bottom size. If Y is the required yield the washer must operate at a specific gravity which satisfies equation 3-13. Figure 3.4 is typical of cumulative weight washability data.

$\hat{SG}$ can be determined by trial and error if the weight washability functions are known. For the initial trial, SG for which W(TS, SG) = Y may be used. This will usually exceed $\hat{SG}$.

Other Washabitity Functions

Properties of the washed product may be determined by mass or energy balances similar to that leading to equation 3-11. Therefore, the heating value and weight fraction sulfur and ash are given by:

$$BTU(TS\text{-}BS, \hat{SG}) = \{BTU(TS, SG) - BTU(BS, SG)[1-F(BS)]\}\frac{1}{F(BS)} \quad (3.11a)$$

$$SUL(TS\text{-}BS, \hat{SG}) = \{SUL(TS, SG) - SUL(BS, SG)[1-F(BS)]\}\frac{1}{F(BS)} \quad (3.11b)$$

$$ASH(TS\text{-}BS, \hat{SG}) = \{ASH(TS, SG) - ASH(BS, SG)[1-F(BS)]\}\frac{1}{F(BS)} \quad (3.11c)$$

3.24 Level 1

Preparation at this level does not involve any washing. Its objective is to satisfy customer specifications or shipping requirements by adjusting coal size and moisture content. Preliminary size control of the mine issue is accomplished by a rotary breaker which also eliminates gross contaminants such as large rocks or timber. The product from the rotary breaker will be referred to as run-of-mine coal. Since the only effect on yield of this breaking operation is the elimination of large rocks which would dilute the coal, and since laboratory tests which are used to ascertain coal characteristics do not account for such dilution, it is consistent to regard this size-controlled product as run-of-mine coal. This most basic level of preparation is therefore regarded as part of the mining process. It is, in fact, part of most modern mines. Hence, "Level 1" preparation is used to refer to additional size control beyond that obtained with the rotary breaker and possible moisture control.

Figure 3.5 is a flow diagram for the Level 1 plant. Run-of-mine coal is classified and crushed to the specified top size with single or double roll crushers. If moisture reduction is necessary a thermal drier, fired by prepared coal, is used. The various stream flow rates are determined as follows. The symbols used are:

Y_o = overall plant yield

Y_j = yield for washer j

$\dot{m}_{ppd}$ = required prepared coal flow rate (tons/hr)

$\dot{m}_i$ = coal flow rate for stream i (tons/hr)

Y_{td} = thermal dryer yield

$\dot{M}$ = rate of moisture removal (tons/hr)

LHV = lower heating value (Btu/ton)

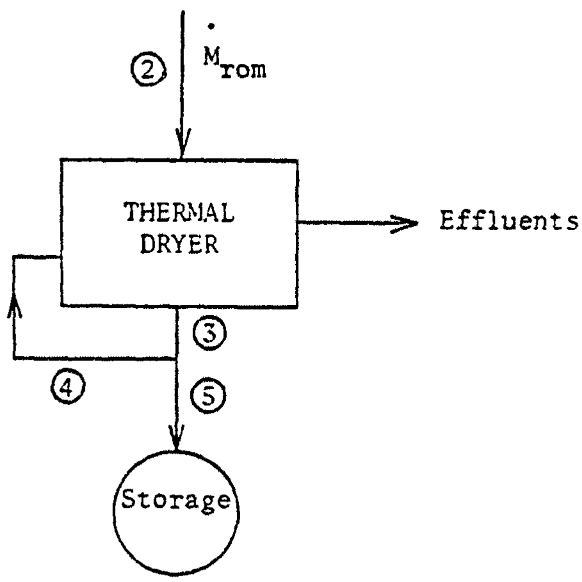


Figure 3.5 Level 1

k_{td} = heat required per unit of moisture removed by thermal dryer (Btu/ton)

M_i = weight fraction moisture in stream i

HHV = higher heating value (Btu/ton)

ASH = weight fraction ash

SUL = weight fraction sulfur

ksul = ratio of sulfur adsorbed by dryed coal to sulfur emitted by combusted coal.

$\underline{}$ = (underscore) indicates moist basis.

The yield of all crushing processes is assumed to be 1.0. Therefore, the overall yield of the level one plant is:

$$Y_o = Y_{td} = \frac{\dot{m}_{ppd}}{\dot{m}_2} \quad (3\text{-}14)$$

Except for the adsorption of a small amount of sulfur, the moisture-free coal which enters the thermal dryer is the same as that which leaves. Therefore,

$$\dot{m}_2 = \dot{m}_3 \quad (3\text{-}15)$$

Also,

$$\dot{m}_3 = \dot{m}_{ppd} + \dot{m}_4 \quad (3\text{-}16)$$

Therefore, the yield may be expressed as:

$$Y_o = \frac{\dot{m}_{ppd}}{\dot{m}_{ppd} + \dot{m}_4} \quad (3\text{-}17)$$

The rate of coal combustion depends on the required rate of moisture removal. If k_{td} is the heat required (Btu) to remove one ton of moisture from the drying coal and $\dot{M}$ is the rate of moisture removal (tons/hr).

$$\underline{\dot{m}_4} = k_{td}\,\dot{M}/\underline{LHV}_{ppd} \quad (3\text{-}18)$$

Notice that this equation determines the moist coal flow rate. This is due to the use of the moist basis lower heating value. $\underline{LHV}_{ppd}$ indicates the actual heat delivered to the moist coal since it claims no credit for latent heat of inherent or surface moisture. Determination of $\underline{LHV}_{ppd}$ is discussed later.

$$\dot{M} = \dot{\underline{m}}_2 - \dot{\underline{m}}_3 = \frac{\dot{m}_2}{1 - M_2} - \frac{\dot{m}_3}{1 - M_3} \quad (3\text{-}19)$$

Using equation 3-15

$$\dot{M} = \dot{m}_2 \frac{M_2 - M_3}{(1-M_2)(1-M_3)} \quad (3\text{-}20)$$

Combining equations 3-18 and 3-20 with

$$B = \frac{M_2 - M_3}{(1-M_2)(1-M_3)} \quad (3\text{-}21)$$

$$\dot{\underline{m}}_4 = k_{td}\, \dot{m}_2 \cdot B / \underline{LHV}_{ppd} \quad (3\text{-}22)$$

But $\dot{m}_2 = \dot{m}_{ppd} + \dot{m}_4$ [from equations 3-15, 3-16] (3-23)

So, $\dot{\underline{m}}_4 = (\dot{M}_{ppd} + \dot{m}_4)\, k_{td} \cdot B / \underline{LHV}_{ppd}$ (3-24)

A mass balance relates m_4 to m_4

$$\dot{m}_4 \cdot (1-M_4) = \dot{m}_4 \quad (3\text{-}25)$$

Noting that $M_4 = M_3 = M_{ppd}$,

$$\dot{\underline{m}}_4 = \dot{M}_4 / (1-M_{ppd}) \quad (3\text{-}26)$$

Substituting this into Equation 3.24 and solving for m_4 yields

$$\dot{m}_4 = \frac{\dot{m}_{ppd}\, k_{td} B}{\underline{LHV}_{ppd}} \left(\frac{1}{1-M_{ppd}} - \frac{k_{td}\, B}{\underline{LHV}_{ppd}}\right)^{-1} \quad (3\text{-}27)$$

The yield from equation 3-17 is therefore:

$$Y_o = Y_{td} \left[1 + \frac{k_{td} \cdot B}{\underline{LHV}_{ppd}} \left(\frac{1}{1-M_{ppd}} - \frac{k_{td} \cdot B}{\underline{LHV}_{ppd}}\right)^{-1}\right]^{-1} \quad (3\text{-}28)$$

Characteristics of the prepared coal may be determined on either a moisture-free or moist basis from characteristics of the raw coal. It is assumed that an ultimate analysis of the moisture-free raw coal and the weight fraction of moisture in the raw coal are available. It is also assumed that the higher heating value of the moisture-free raw coal is known. Then, in our notation, the following quantities are known directly; SUL_{rom}, ASH_{rom}, H, O, N, C, and M_{rom}. These characteristics may also be expressed on a moist basis.

$$\underline{SUL}_{rom} = SUL_{rom}\ (1-M_{rom}) \tag{3-29}$$

$$\underline{ASH}_{rom} = ASH_{rom}\ (1-M_{rom}) \tag{3-30}$$

$$\underline{HHV}_{rom} = HHV_{rom}\ (1-M_{rom}) \tag{3-31}$$

On a dry basis no change would be expected due to moisture removal by the thermal dryer. This is true except for the adsorption of SO_2 from the thermal dryer combustion gases onto the drying coal. Define k_{sul} as the fraction of generated SO_2 which is adsorbed. Then

$$SUL_{ppd} = SUL_{rom}\ (1 + k_{sul} \cdot \frac{\dot{m}_4}{\dot{m}_2}) \tag{3-32}$$

Using equations 3-22 and 3-25

$$\frac{\dot{m}_4}{\dot{m}_2} = \frac{k_{td}\ (1-Mppd)B}{\underline{LHV}\ ppd} \tag{3-33}$$

Therefore,

$$SUL_{ppd} = SUL_{rom}\ [1 + \frac{k_{sul}\ k_{td}\ (1-M_{ppd})B}{\underline{LHV}\ ppd}] \tag{3-34}$$

Assuming HHV_{rom} is known, $\underline{LHV}_{ppd}$ may be determined as follows (Btu/

$$HHV_{ppd} = HHV_{rom} \tag{3-35}$$

$$LHV_{ppd} = HHV_{ppd} - \frac{H}{2} \cdot 18 \cdot 1020 \tag{3-36}$$

$$\underline{LHV}_{ppd} = LHV_{ppd}\ (1 - M_{ppd}) - M_{ppd} \cdot 1020 \tag{3-37}$$

H is the weight fraction of hydrogen in the moisture free coal.

Example for Level 1

Data: $\dot{m}_{ppd}$ = 1000 tons/hr	H = 0.05	ASH_{rom} = 0.20
k_{td} = 4.0 10^6 Btu/ton	k_{sul} = 0.32	
M_{rom} = 0.25	HHV_{rom} = 12500 Btu/lb	
M_{ppd} = 0.10	SUI_{rom} = 0.03	

$$HHV_{ppd} = HHV_{rom} = 12500$$

$$LHVppd = HHV_{ppd} - 9180 \cdot H = 12500 - 459 = 12041$$

$$\underline{LHV}_{ppd} = LHV_{ppd}\ (1 - M_{ppd}) - M_{ppd}\ 1020$$

$$= 12041\ (1-0.10) - 0.10(1020) = 10735 \text{ Btu/ lb.}$$

$$= 21.5 \cdot 10^6 \text{ Btu/ton}$$

$$Y_{td} = [1 + \frac{k_{td} \cdot B}{\underline{LHV}_{ppd}} (\frac{1}{1 - M_{ppd}} - \frac{k_{td} \cdot B}{\underline{LHV}_{ppd}})^{-1}]^{-1}$$

$$B = \frac{M_{rom} - M_{ppd}}{(1-M_{rom})(1-M_{ppd})}$$

$$= \frac{0.25 - 0.10}{(1-0.25)(1-0.10)} = 0.193$$

$$Y_{td} = [1 + \frac{(4.0 \cdot 10^6)(0.193)}{[21.5 \cdot 10^6]} (\frac{1}{1-0.10} - \frac{4.0 \cdot 10^6 (0.193)}{[21.5 \cdot 10^6]})^{-1}]^{-1} = 0.98$$

$$SUL_{ppd} = SUL_{rom}\ [1 + \frac{k_{sul}\ k_{td} (1-M_{ppd}) B}{\underline{LHV}_{ppd}}]$$

$$= 0.03\ [1 + \frac{(0.32)(4.0 \cdot 10^6)(1-0.10)(0.193)}{21.5 \cdot 10^6}]$$

$$= 0.0303$$

3.25 Level 2

The simplest washing device, a jig, employs pulsating water or air to create a fluid-like bed of moving coal particles. Eventually the heavier fractions settle to the bottom of the jig where they can be discarded as refuse. Such a device is used for coarse coal washing in the level 2 plant. The level 2 product is a combination of the washed coarse coal and the unwashed fine coal. Figure 3.6 indicates the basic process operations and flows.

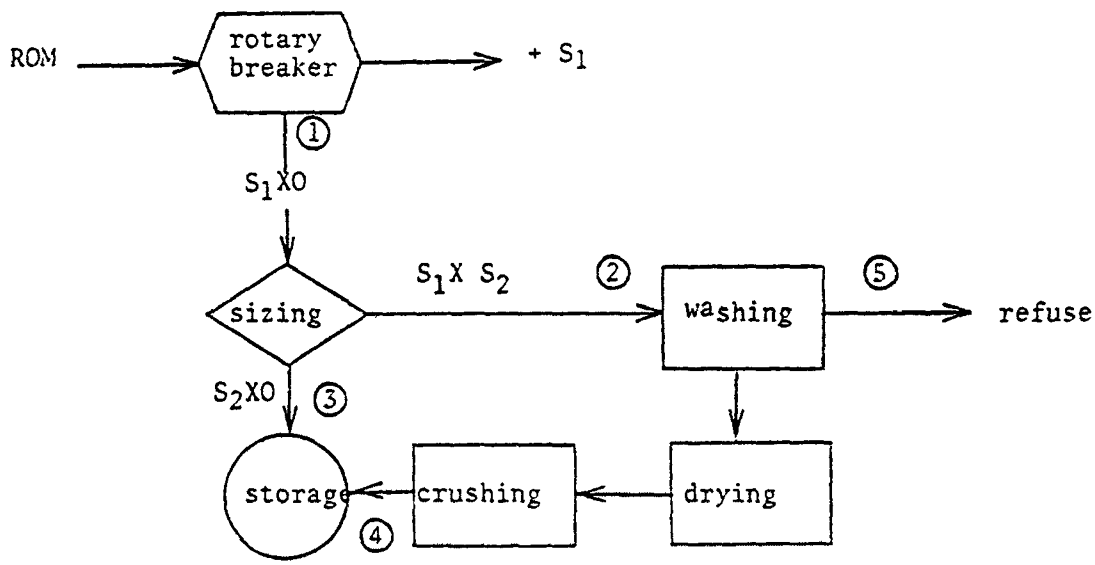


Figure 3.6 Level 2

$$Y_o = [1 - F(S_2)] + F(S_2)Y_1 \quad (3\text{-}38)$$

$$Y_1 = \frac{Y_o - 1 + F(S_2)}{F(S_2)} \quad (3\text{-}39)$$

$$\dot{m}_1 = \dot{m}_{ppd}/Y_o \quad (3\text{-}40)$$

$$\dot{m}_2 = \dot{m}_1 \cdot F(S_2) \quad (3\text{-}41)$$

$$\dot{m}_3 = \dot{m}_1[1 - F(S_2)] \quad (3\text{-}42)$$

$$\dot{m}_4 = Y_1 \cdot m_2 \quad (3\text{-}43)$$

$$\dot{m}_5 = \dot{m}_2(1-Y_1) \quad (3\text{-}44)$$

$$BTU_{ppd} = [BTU(S_2,\ 2.0)[1-F(S_2)] + BTU(S_1 - S_2,\ \hat{S}G) \cdot F(S_2) \cdot Y_1] \frac{1}{Y_o} \quad (3\text{-}45)$$

$$SUL_{ppd} = [SUL(S_2,\ 2.0)[1-F(S_2)] + SUL(S_1 - S_2,\ \hat{S}G) \cdot F(S_2) \cdot Y_1] \frac{1}{Y_o} \quad (3\text{-}46)$$

$$ASH_{ppd} = [ASH(S_2,\ 2.0)[1-F(S_2)] + ASH(S_1 - S_2,\ \hat{S}G) \cdot F(S_2) \cdot Y\ ] \frac{1}{Y_o} \quad (3\text{-}47)$$

Example for Level 2

Size distribution data:

SIZE	FRACTION OVERSIZE
3 in.	0.000
1 in.	0.175
1/2 in.	0.362
1/4 in.	0.530
10 mesh (0.069")	0.785
28 mesh	0.905
100 mesh	0.964

Determination of F(x):

$F(1") = 0.175 \qquad F(0.069") = 0.785$

$\log(1) = 0.000 \qquad \log(0.069) = -1.161$

$\log\log\frac{1}{0.175} = -0.121 \qquad \log\log\frac{1}{0.785} = -0.978$

$$\alpha = \frac{-0.121 - (-0.978)}{0.000 - (-1.161)} = \frac{0.854}{1.161} = 0.738$$

$$x_o = 0.069[-\ell n\ (0.785)]^{-1/0.738} = 0.472$$

Therefore

$$F(x) = e^{-\left(\frac{x}{0.472}\right)^{0.738}}$$

For example, $F(0.25) = e^{-\left(\frac{0.25}{0.472}\right)^{0.738}} = 0.535$ which agrees with the data above.

Cumulative washability data:

	TS = 5.0"				TS = 0.25"			
SG FLOAT	W	%S	% ASH	BTU/LB	W	%S	%ASH	BTU/LB
1.5	0.7634	0.99	10.37	13065	0.7564	0.92	6.99	13588
1.6	0.8308	1.08	12.02	12796	0.8096	0.98	8.40	13343
1.7	0.8643	1.20	12.96	12618	0.8471	1.06	9.63	13117
1.9	0.8975	1.33	14.07	12385	0.8835	1.15	11.07	12830
TOTAL	1.0000	1.36	20.20	11316	1.0000	1.29	18.43	11561

Let $S_2 = 0.25''$ and $Y_o = 0.90$.

For an overall plant yield of 0.90, the washer yield must be:

$$Y_1 = \frac{Y_o - 1 + F(S_2)}{F(S_2)} = \frac{0.90 - 1 + 0.530}{0.530} = 0.817$$

The specific gravity of separation for the washer, $\hat{SG}$, is calculated as follows:

Assume $\hat{SG} = 1.57$ (value corresponding to $W(3, \hat{SG}) = 0.811$). Then from Equation 3.13

$$\bar{Y} = Y_1 = \{W(3, 1.57) - W(0.25, 1.57)[1-F(0.25)]\} \frac{1}{F(0.25)}$$

$$= \{0.811 - 0.794(1 - 0.53)\} \frac{1}{0.53} = 0.826 \sim 0.811$$

For SG = 1.55

$$Y_1 = \{0.797 - 0.783(1 - 0.53)\} \frac{1}{0.53} = 0.809$$

This is close enough. The value $\hat{SG} = 1.55$ is used for subsequent calculations. The washer product has the following characteristics (dry basis):

$$BTU(3''- 1/4'',1.55) = \{BTU(3'', 1.55)- BTU(1/4'',1.55)[1-F(1/4'')]\}\frac{1}{F(1/4'')}$$

$$= \{12931 - 13466\cdot[1-0.53]\} \frac{1}{0.53} = 12{,}457 \text{ Btu/lb}$$

$$SUL(3''-1/4'', 1.55)= \{SUL(3'',1.55)- SUL(1/4'',1.55)[1-F(1/4'')]\} \frac{1}{F(1/4'')}$$

$$= \{0.0104 - 0.0095(1 - 0.53)\} \frac{1}{0.53} = 0.0112$$

$$ASH (3''-1/4'',1.55) = \{.1120-0.0770(1 - 0.53)\} \frac{1}{0.53} = 0.143$$

Characteristics of the prepared coal are:

$$BTU_{ppd} = [BTU(1/4, 2.0)[1-F(1/4'')] + BTU(3''-1/4'',1.55)F(1/4)\cdot Y_1] \frac{1}{Y_o}$$

$$= [11561 (1-0.53) + 12457(0.53)\cdot 0.811] \frac{1}{0.90}$$

$$= 11{,}987$$

$$SUL_{ppd} = [SUL(1/4,2.0)[1-F(1/4)] + SUL(3''-1/4'',1.55)\cdot F(1/4)\cdot 0.811] \frac{1}{0.90}$$

$$= [0.0129(1-0.53) + 0.0112 (0.53)(0.811)] \frac{1}{0.90}$$

$$= 0.0121$$

$$ASH_{ppd} = [ASH\ (1/4, 2.0)(1-F(1/4)) + ASH(3''-1/4'', 1.55)\cdot F(1/4)\cdot Y_1]\ \frac{1}{Y_o}$$

$$= [0.1843\ (1-0.53) + 0.143(0.53)(0.811)]\ \frac{1}{0.90}$$

$$= 0.165$$

These are on a dry basis. Note that in this example, the washed sizes correspond to available data. If they had not, interpolation between sizes for which data are available would be required.

3.2.6 Level 3 - Washing of Coarse and Medium Coal Sizes

The Level 3 plant has two washing circuits. The coarse coal, sizes S_1 to S_2, is washed in a jig type washer while the intermediate coal, S_2, S_3 is washed in a dense media washer. The unwashed fines are mixed with the two washed streams to form the product. Only mechanical dewatering is used. Figure 3.7 represents this configuration.

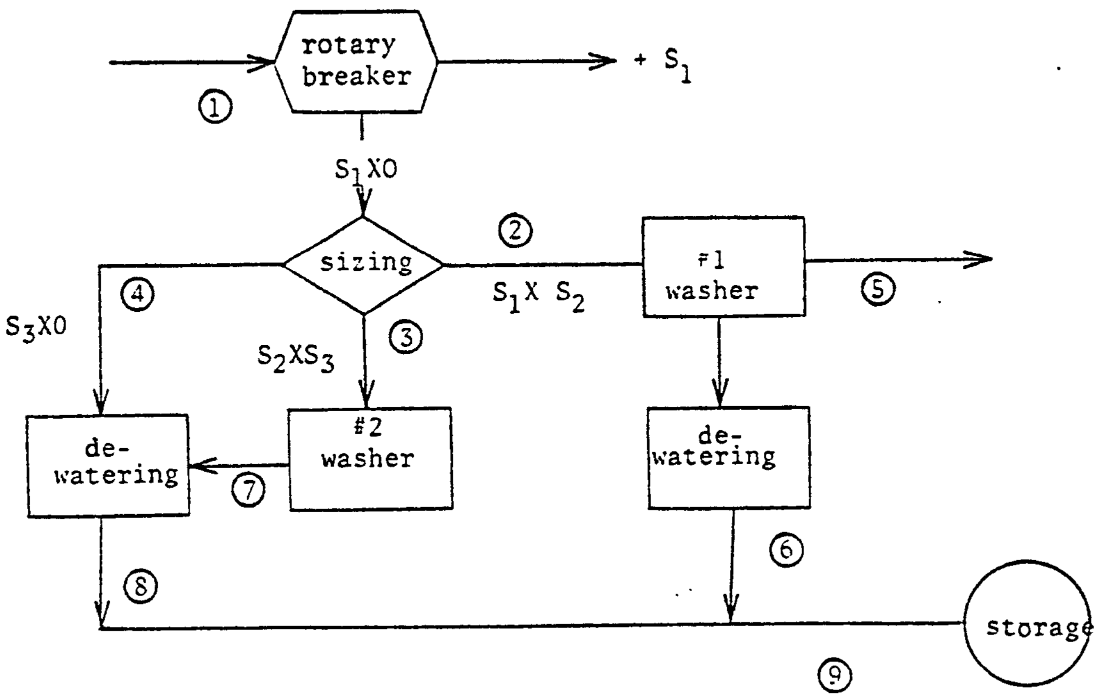


Figure 3.7 Level 3

$$Y_o = [1-F(S_3)] + [F(S_3) - F(S_2)]\ Y_2 + F(S_2)\cdot Y_1 \qquad (3\text{-}48)$$

Let $Y_1 = Y_2 = Y'$. (3-49)

$$\text{Then } Y_o = [1- F(S_3)] + [F(S_3) - F(S_2)]\ Y' + F(S_2)\cdot Y'$$

$$= 1 - F(S_3) + F(S_3)\cdot Y' \qquad (3\text{-}50)$$

$$Y' = \frac{Y_o - 1 + F(S_3)}{F(S_3)} \qquad (3\text{-}51)$$

$$P_{ppd} = \{P(S_3,\ 2.0)[1-F(S_3)] + P(S_3-S_2,\ \hat{S}G_2)\cdot Y'\cdot[F(S_3)-F(S_2)] + P(S_2,\ \hat{S}G_1)\cdot Y'\cdot F(S_2)\}\frac{1}{Y_o} \qquad (3\text{-}52)$$

where P_{ppd} is some property of the prepared coal.

Example for Level 3

This is similar to Level 2 except that 2 washers are used. $\hat{S}G$ must be determined for each. Washability data for top sizes at least as large as S_1 and as small S_3 are required. For S_3 = 28 mesh, the following washability applies.

TS = 28 mesh = 0.0232"

SG FLOAT	W	%S	%ASH	BTU/LB
1.5	70.73	0.96	7.16	13520
1.6	78.01	1.01	9.02	13196
1.7	82.13	1.04	10.23	12967
1.9	86.25	1.03	11.73	12658
TOTAL	100.00	1.43	18.99	11284

$$Y' = \frac{Y_o - 1 + F(0.0232)}{(F(0.0232)}$$

$$F(0.0232) = e^{-\left(\frac{0.0232}{0.472}\right)^{0.738}} = 0.90$$

$$Y' = \frac{0.9 - 1 + 0.9}{0.9} = 0.89$$

Washer 1

Assume $\hat{SG}_1$ = 1.85 (at this value W = 0.89 for TS = 3.0) Checking with equation 3.13.

$$Y_1 = \{W(3, 1.85) - W(0.25, 1.85)[1 - F(0.25)]\} \frac{1}{F(0.25)}$$

$$= [0.89 - 0.874(1 - 0.535)] \frac{1}{0.535} = 0.904 \sim 0.89$$

Washer 2

$\hat{SG} = 1.9 \rightarrow Y_2 = 0.8835$ is the highest SG for which W is available. One could extrapolate beyond 1.9 but this is a reasonable first approximation anyway.

$$Y_2 = \{W(0.25, 1.9)[1-F(0.25)] - W(28m, 1.9)[1-F(0.0232)]\} \frac{1}{F(0.0232)-F(0.25)}$$

$$= [0.8835(1-.535)-0.8625(1-0.9)] \frac{1}{0.9-0.535} = 0.889$$

Therefore $\hat{SG}_1 = 1.85$, $\hat{SG}_2 = 1.9$ are used.

The washed coal characteristics:

Washer 1 $\hat{SG}$ = 1.85

$$BTU(3''-1/4'', 1.85) = \{BTU(3'',1.85)-BTU(1/4'',1.85)[1-F(1/4'')]\} \frac{1}{F(1/4'')}$$

$$= [12443 - 12902(0.465)] \frac{1}{0.535}$$

$$= 12044 \text{ BTU/LB}$$

$$SUL(3''-1/4'',1.85) = \{SUL(3'',1.85) - SUL(1/4'',1.85)[1-F(1/4'')]\} \frac{1}{F(1/4'')}$$

$$= [1.30 - 1.13(0.465)] \frac{1}{0.535} = 1.45\%$$

$$ASH(3''-1/4'', 1.85) = \{ASH(3'',1.85)-ASH(1/4'',1.85)[1-F(1/4)]\} \frac{1}{F(1/4)}$$

$$= [13.79 - 10.71(0.465)] \frac{1}{0.535} = 16.47\%$$

Washer 2 $\hat{SG}$ = 1.90

$$BTU(1/4''-0.0232'', 1.90) = \{BTU(1/4,1.9)[1-F(1/4)]-BTU(0.0232,1.9)[1-F(0.0232)]\} \cdot \frac{1}{F(0.0232)-F(1/4)}$$

$$= [12830(0.465)-12658(0.1)] \frac{1}{0.365} = 12877 \text{ Btu/lb}$$

$$SUL(1/4''-0.0232'',1.90) = \{SUL(1/4,1.9)[1-F(1/4)]-SUL(0.0232,1.9)[1-F(0.0232)]\} \cdot \frac{1}{F(0.0232)-F(1/4)}$$

$$= [1.15(0.465)-1.09(.1)]\frac{1}{0.365} = 1.17\%$$

$$ASH(1/4''-0.0232'',1.90) = \{ASH(1/4,1.9)[1-F(1/4)]-ASH(0.0232,1.9)[1-F(0.0232)]\} \cdot \frac{1}{F(0.0232)-F(1/4)}$$

$$= [14.07(0.465)-11.07(.1)]\frac{1}{0.365} = 14.89\%$$

The prepared coal characteristics are:

$$BTU_{ppd} = \{BTU(0.0232,2.0)[1-F(0.0232)]+BTU(1/4-0.0232,1.9)(Y_2)[F(0.0232)-F(1/4)] + BTU(3''-1/4'',1.85)(Y_1)[F(0.25)]\}\frac{1}{0.90}$$

$$= \{11284(1-0.9) + 12850(0.89)[0.90 - 0.535] + 12044(0.89)[0.535]\}\frac{1}{0.9} = 12264 \text{ Btu/lb}$$

$$SUL_{ppd} = \{SUL(0.0232,2.0)[1-F(0.0232)] + SUL(1/4-0.0232,1.9)Y_2[F(0.0232)-F(1/4)] + SUL(3 - 1/4,1.85)Y_1[F(0.25)]\}\frac{1}{0.90}$$

$$= \{0.0143(1-0.9) + 0.0116(.89)(0.9-0.535) + 0.0145(0.89)(0.535)\}\frac{1}{0.90}$$

$$= 0.0135 \text{ or } 1.35\%$$

$$ASH_{ppd} = \{ASH(0.0232,2.0)[1-F(0.0232)] + ASH(1/4-0.0232,1.9)Y_2[F(0.0232) - F(0.25)] + ASH(3-1/4,1.85)\ Y_1[F(0.25)]\}\frac{1}{0.90}$$

$$= \{0.1899[1-0.9] + 0.1437(0.89)(0.9-0.535)+0.1647(0.89)(0.535)\}\frac{1}{0.90}$$

$$= 0.160 \text{ or } 16\%$$

3.27 Level 4, Complete Washing

In this plant all coal sizes are washed. The fines, S_3 x 0 and the intermediate coal, S_2 x S_3, are thermally dried by hot gases from the combustion of cleaned coal in a thermal dryer. In addition to the effect on moisture content, the thermal dryer results in an increase in sulfur content due to adsorption of SO_2 from the hot flue gases. Also, the net yield is reduced due to combustion of the cleaned coal. The final product is a mixture of the dried coals and the mechanically dewatered coarse coal. Figure 3.8 represents

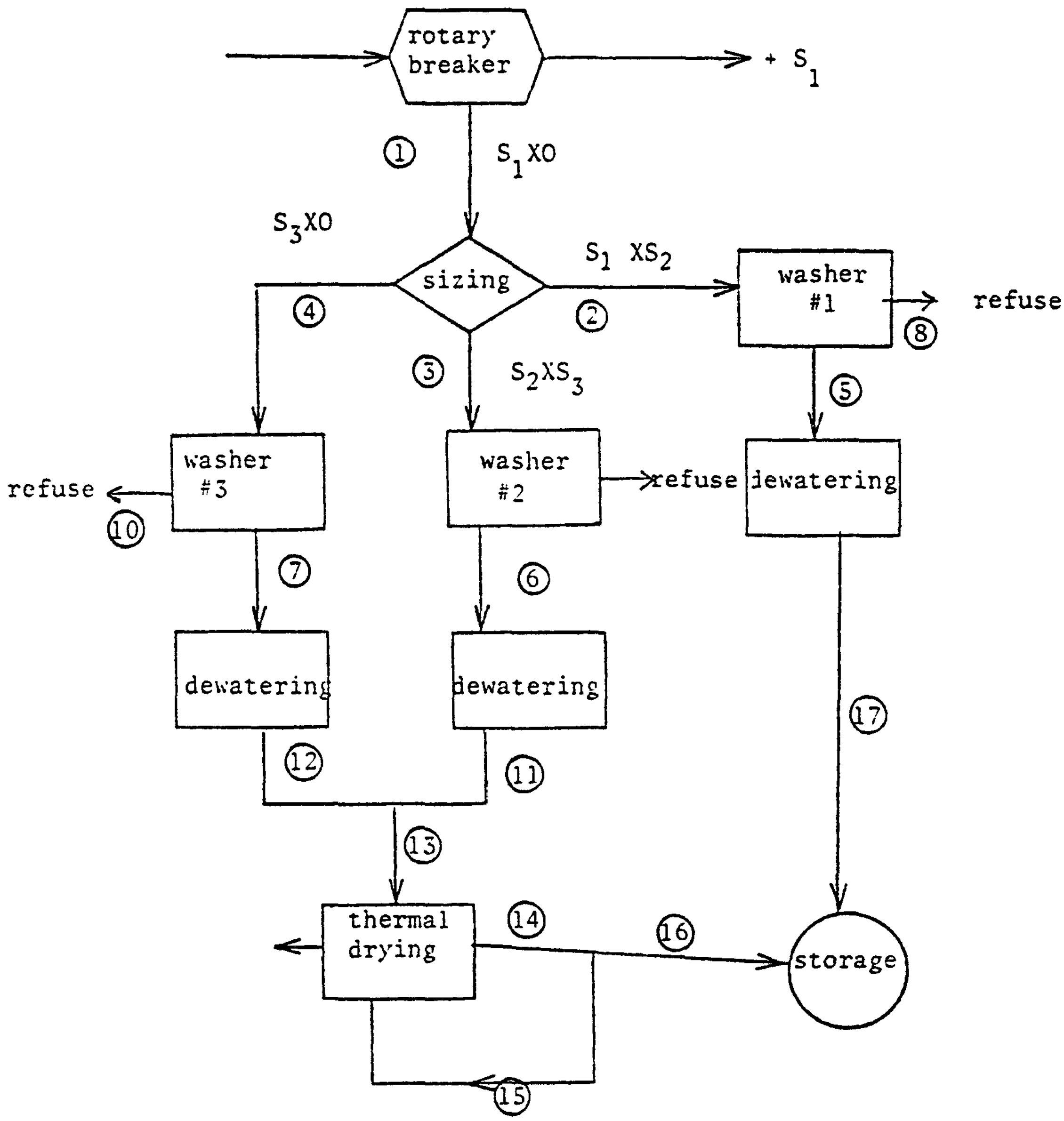


Figure 3.8 Level 4

$$= 0.90 \{0.535 + 0.957 [0.465]\}^{-1}$$

$$= 0.92$$

The specific gravity corresponding to this yield and associated washability data are found through linear extrapolation of the available data. Using equation 3.13 it can be verified that:

$$SG_1 = 1.97$$

$$SG_2 = 2.05$$

$$SG_3 = 2.18$$

The extrapolations are shown on the accompanying graphs (Figures 3.9-3.12).

Properties of the washed coals are:

<u>Washer 1</u>

$$BTU(3''\text{-}1/4'',1.97) = \{BTU(3'',1.97) - BTU(1/4'',1.97)[1-F(1/4'')]\}\frac{1}{F(1/4'')}$$

$$= [12300 - 12580(1 - 0.535)]\frac{1}{0.535} = 12057 \text{ Btu/lb}$$

$$SUL(3''\text{-}1/4'',1.97) = [1.375-1.18(1-0.535)] \div 0.535 = 1.54\%$$

$$ASH(3''\text{-}1/4'',1.97) = [14.4 - 11.6(1-0.535)] \div 0.535 = 16.8\%$$

<u>Washer 2</u>

$$BTU(1/4''\text{-}28mesh,2.05) = \{BTU(1/4'',2.05)[1-F(1/4'')] - BTU(0.0232)[1-F(0.0232)]\} \cdot \frac{1}{F(0.0232)-F(1/4)}$$

$$= [12615(0.465) - 12425(0.1)]\frac{1}{0.365} = 12667$$

$$SUL(1/4''\text{-}28mesh,2.05) = [1.20(0.465)-1.12(0.1)]\frac{1}{0.365} = 1.22\%$$

$$ASH(1/4''\text{-}28mesh,2.05) = [11.9(0.465)-12.5(0.1)]\frac{1}{0.365} = 11.74\%$$

<u>Washer 3</u>

BTU(28mesh, 2.18) = 12225

SUL(28mesh, 2.18) = 1.17

ASH(28mesh, 2.18) = 13.8

Properties of the thermal dryer feed stream:

Figure 3.9

WEIGHT WASHABILITY

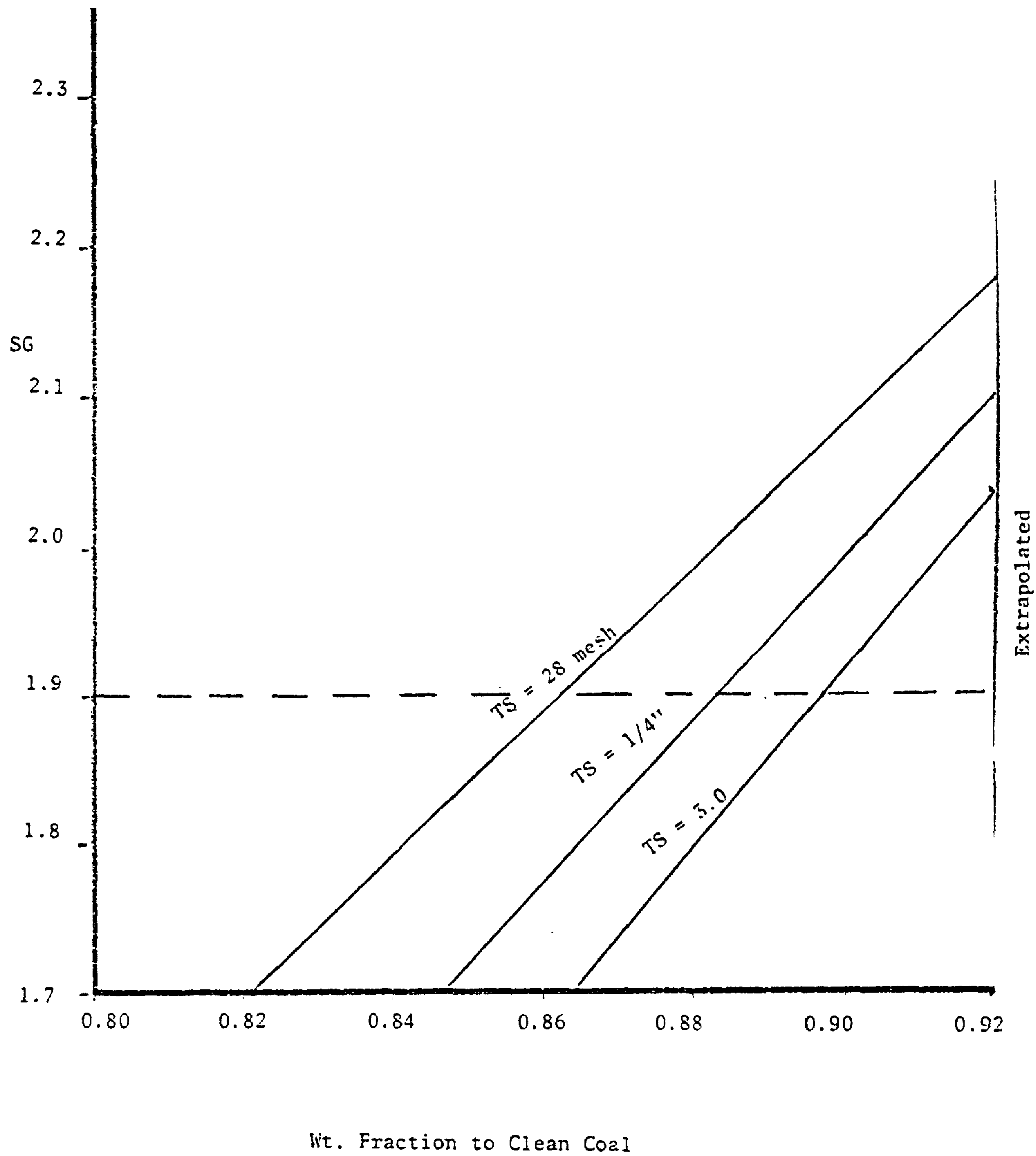


Figure 3.10

ASH WASHABILITY

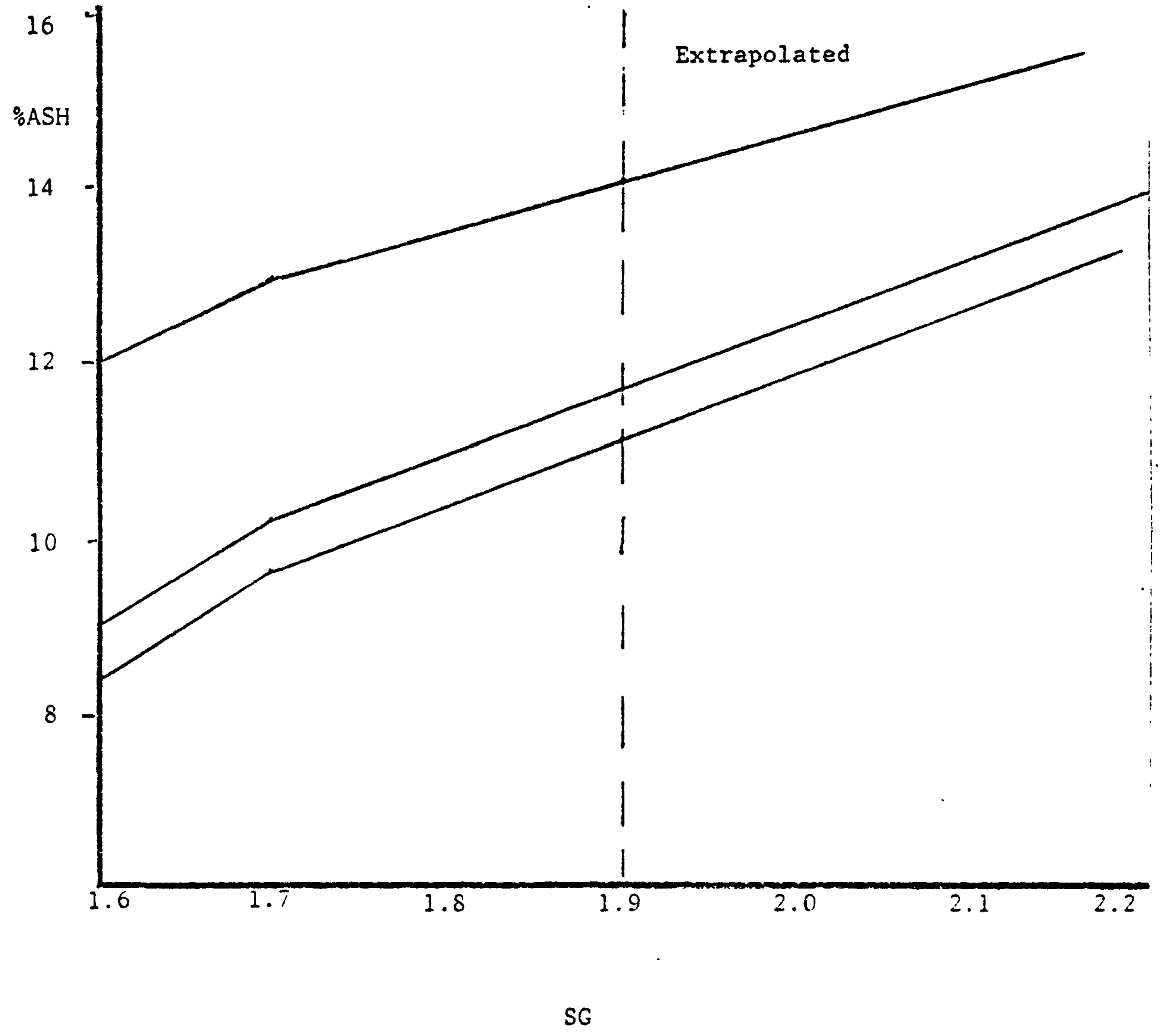
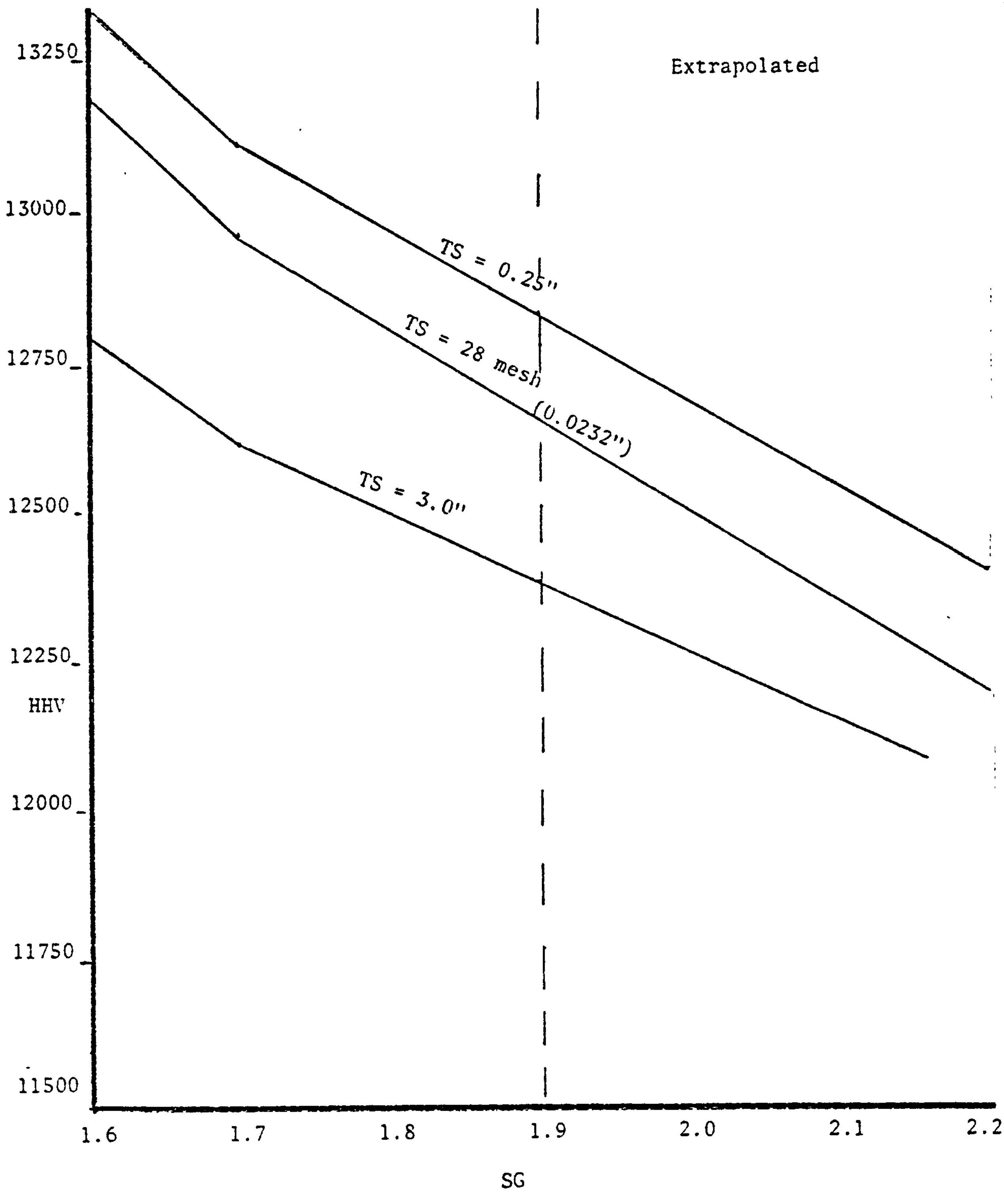


Figure 3.11

BTU WASHABILITY



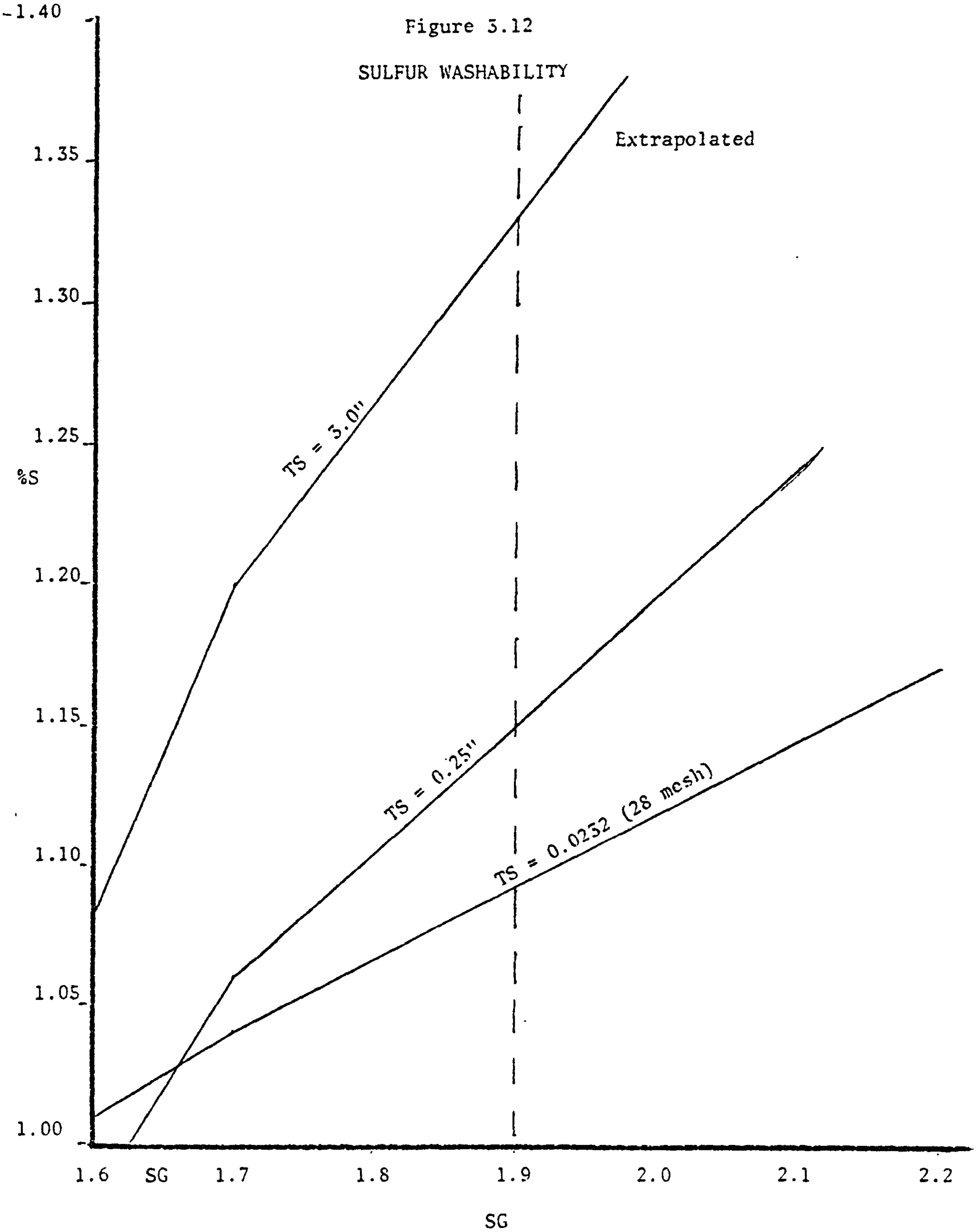


Figure 3.12
SULFUR WASHABILITY
Extrapolated
TS = 3.0"
TS = 0.25"
TS = 0.0232 (28 mesh)
%S
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
1.6
SG
1.7
1.8
1.9
2.0
2.1
2.2
SG

$$BTU_{13} = \frac{1}{Y'[1-F(S_2)]}\{BTU(28mesh,2.18)\cdot Y'\cdot[1-F(28mesh)]+BTU(1/4''-28mesh,2.05)\cdot Y'\cdot [F(28mesh)-F(1/4'')]\}$$

$$= \frac{1}{0.92(1-0.0535)}\{12225(0.92)(1-0.9) + 12667\ (0.92)(0.9-0.535)\}$$

$$= 12572$$

$$SUL_{13} = \frac{1}{0.92(0.465)}[1.17(0.92)(0.1)+1.22(0.92)(0.9-0.535)] = 1.21\%$$

$$ASH = 2.34[13.8(0.092) + 11.74(0.92)(0.365)] = 12.20\%$$

The properties of the dried coal are:

$$BTU_{16} = BTU_{13} = 12572 \text{ Btu/lb} \quad ASH_{16} = ASH_{13} = 12.20\%$$

$$SUL_{16} = SUL_{1.3}[1 + \frac{k_{sul}k_{td}(1-M_{ppd})B}{LHV_{ppd}}]$$

$$= 1.21[1 + \frac{(0.32)(4.0\ 10^6)(1-0.10)(0.193)}{10800\cdot 2000}] = 1.22\%$$

The prepared coal properties are:

$$BTU_{ppd} = \{[1-0.535](12572)(0.92)(0.957) + 12057(0.92)(0.535)\}\frac{1}{0.9}$$

$$= 12313 \text{ Btu/lb}$$

$$SUL_{ppd} = \{(0.465)(1.22)(0.92)(0.957) + 1.54(0.92)(0.535)\}\frac{1}{0.9}$$

$$= 1.40\%$$

$$ASH_{ppd} = \{0.465(12.2)(0.92)(0.957) + 16.8(0.92)(0.535)\}\frac{1}{0.9}$$

$$= 14.74\%$$

this configuration.

$$Y_o = [F(S_2)]\cdot Y_1 + \{[F(S_3)-F(S_2)]\cdot Y_2 + [1-F(S_3)]\cdot Y_3\}\ Y_{td} \quad (3\text{-}53)$$

let $Y_1 = Y_2 = Y_3 = Y'$

$$Y_o = Y'F(S_2) + Y_{td}\ \{Y'[1-F(S_2)]\} \quad (3\text{-}54)$$

$$= Y'\{F(S_2) + Y_{td}[1-F(S_2)]\} \quad (3\text{-}55)$$

$$Y' = Y_o\{F(S_2) + Y_{td}[1-F(S_2)]\}^{-1} \quad (3\text{-}56)$$

Properties of the input stream to the thermal dryer: (dry basis)

$$P_{13} = \frac{1}{Y\cdot[1-F(S_2)]}\{P(S_3,\hat{S}G_3)\cdot Y'\cdot[1-F(S_3)]+P(S_2-S_3,\hat{S}G_2)\cdot Y'\cdot[F(S_3)-F(S_2)]\} \quad (3\text{-}57)$$

The properties of the dried stream, P_{16}, are determined as for Level 1. The prepared coal properties are then:

$$P_{ppd} = \{[1-F(S_2)]\cdot P_{16}\cdot Y'\cdot Y_{td} + P(S_1-S_2,\ \hat{S}G_1)\cdot Y'\cdot F(S_2)\}\ \frac{1}{Y_o} \quad (3\text{-}58)$$

Example for Level 4

Data required in addition to that used for the level three analysis is:

$k_{td} = 4.0\cdot 10^6$ Btu required/ton moisture removed

$k_{sul} = 0.32$ lbs adsorbed/lb SO_2 emitted

$M_{rom} = 0.25$

$M_{ppd} = 0.10$

$HHV_{rom} = 11316$

$H = 0.05$

Based on these values Y_{td} is calculated as for example 1:

$Y_{td} = 0.957$

The washer yields for washers 1, 2, and 3 are:

$$Y' = Y_o\ \{F(S2) + Y_{td}[1-F(S2)]\}^{-1}$$

The specific gravity corresponding to this yield and associated washability data are found through linear extrapolation of the available data. Using equation 3.13 it can be verified that:

$SG_1 = 1.97$

$SG_2 = 2.05$

$SG_3 = 2.18$

The extrapolations are shown on the accompanying graphs (Figures 3.9 through 3.12).

Properties of the washed coals are:

Washer 1

$$BTU(3''-1/4'', 1.97) = \{BTU(3'',1.97) - BTU(1/4'',1.97)[1-F(1/4'')]\} \frac{1}{F(1/4'')}$$

$$= [12300-12580(1.-0.535)] \frac{1}{0.535} = 12057 \text{ Btu/lb}$$

$$SUL(3''-1/4'', 1.97) = [1.375-1.18(1-0.535)] \div 0.535 = 1.54\%$$

$$ASH(3''-1/4'', 1.97) = [14.4 - 11.6(1-0.535)] \div 0.535 = 16.8\%$$

Washer 2

$$BTU(1/4''\text{-}28mesh, 2.05) = \{BTU(1/4'',2.05)[1-F(1/4'')] - BTU(0.0232)[1-F(0.0232)]\} \cdot \frac{1}{F(0.0232)\ F(1/4)}$$

$$= [12615(0.465)-12425(0.1)] \frac{1}{0.365} = 12667$$

$$SUL(1/4''\text{-}28mesh, 2.05) = [1.20(0.465)-1.12(0.1)] \frac{1}{0.365} = 1.22\%$$

$$ASH(1/4''\text{-}28mesh, 2.05) = [11.9(0.465)-12.5(0.1)] \frac{1}{0.365} = 11.74\%$$

Washer 3

BTU(28 mesh, 2.18) = 12225

SUL(28 mesh, 2.18) = 1.17

ASH(28 mesh, 2.18) = 13.8

Properties of the thermal dryer feed stream:

$$BTU_{13} = \frac{1}{Y'[1-F(S_2)]} \{BTU(28mesh, 2.18) \cdot Y' \cdot [1-F(28mesh)] + BTU(1/4''-28mesh, 2.05) \cdot Y' \cdot [F(28mesh) - F(1/4'')]\}$$

$$= \frac{1}{0.92(1-0.535)} \{12225(0.92)(1-0.9) + 12667(0.92)(0.9-0.535)\}$$

$$= 12572$$

$$SUL_{13} = \frac{1}{0.92(0.465)} [1.17(0.92)(0.1) + 1.22(0.92)(0.9-0.535)] = 1.21\%$$

$$ASH = 2.34[13.8(0.092) + 11.74(0.92)(0.365)] = 12.20\%$$

The properties of the dried coal are:

$$BTU_{16} = BTU_{13} = 12572 \text{ Btu/lb} \quad ASH_{16} = ASH_{13} = 12.20\%$$

$$SUL_{16} = SUL_{13}[1 + \frac{(0.32)(4.0 \cdot 10^6)(1-0.10)(0.193)}{10800 \cdot 2000} = 1.22\%$$

The prepared coal properties are:

$$BTU_{ppd} = \{[1-0.535](12572)(0.92)(0.957) + 12057(0.92)(0.535)\} \frac{1}{0.9}$$

$$= 12313 \text{ Btu/lb}$$

$$SUL_{ppd} = \{(0.465)(1.22)(0.92)(0.957) + 1.54(0.92)(0.535)\} \frac{1}{0.9}$$

$$= 1.40\%$$

$$ASH_{ppd} = \{0.465(12.2)(0.92)(0.957) + 16.8(0.92)(0.535)\} \frac{1}{0.9}$$

$$= 14.74\%$$

APPENDIX C

COMPARISON OF PCC AND PARTIAL FGD DATA

Table C.1 Data on PCC and Partial FGD

Plant	1980 Emissions $\#SO_2$/MMBtu	Coal Cleaning Wt. Recovery	Coal $\#SO_2$/MMBtu	%S Reduction	Coal Cost $/MMBtu	PCC Cost $/Ton SO_2	Equiv. FGD Cost $/Ton SO_2
A	5.41	ROM	5.99	-	1.501	-	-
		.800	5.12	14.6	2.098	1366	525
B	5.13	ROM	9.93	-	1.508	-	-
		.800	6.54	34.1	2.109	355	731
C	4.22	ROM	4.94	-	1.512	-	-
		.800	3.01	39.2	2.110	616	1091
E	4.40	ROM	4.31	-	1.512	-	-
		.800	3.27	24.1	2.115	1162	978
F	4.41	ROM	5.53	-	1.500	-	-
		.800	4.08	26.2	2.091	818	815
G	5.10	ROM	6.39	-	1.499	-	-
		.800	4.88	23.7	2.087	778	746
H	8.22	ROM	6.72	-	1.500	-	-
		.800	3.95	41.2	2.090	426	979
I	6.44	ROM	6.39	-	1.499	-	-
		.800	4.88	23.7	2.087	778	589
J	2.65	ROM	3.85	-	1.481	-	-
		.800	2.54	34.1	2.053	871	1294
K	6.49	ROM	7.35	-	1.487	-	-
		.800	6.04	17.7	2.063	884	594
M	5.77	ROM	6.73	-	1.542	-	-
		.800	4.87	27.6	2.159	664	754
N	8.16	ROM	8.69	-	1.317	-	-
		.800	5.86	32.6	1.930	434	674
O	6.87	ROM	9.15	-	1.317	-	-
		.800	6.30	31.1	1.937	435	699
P	3.45	ROM	4.14	-	1.504	-	-
		.800	2.75	33.5	2.094	851	1162
Q	5.47	ROM	5.50	-	1.500	-	-
		.800	4.91	10.6	2.099	2057	649
R	4.78	ROM	5.99	-	1.501	-	-
		.800	5.12	14.6	2.098	1366	630
S	3.36	ROM	4.94	-	1.512	-	-
		.800	3.01	39.2	2.110	616	976
T	6.02	ROM	7.25	-	1.530	-	-
		.800	5.08	29.9	2.147	569	597
U	5.08	ROM	4.86	-	1.495	-	-
		.800	2.43	50.0	2.082	483	1231
V	4.42	ROM	6.10	-	1.317	-	-
		800	4.09	33.0	1.932	611	854

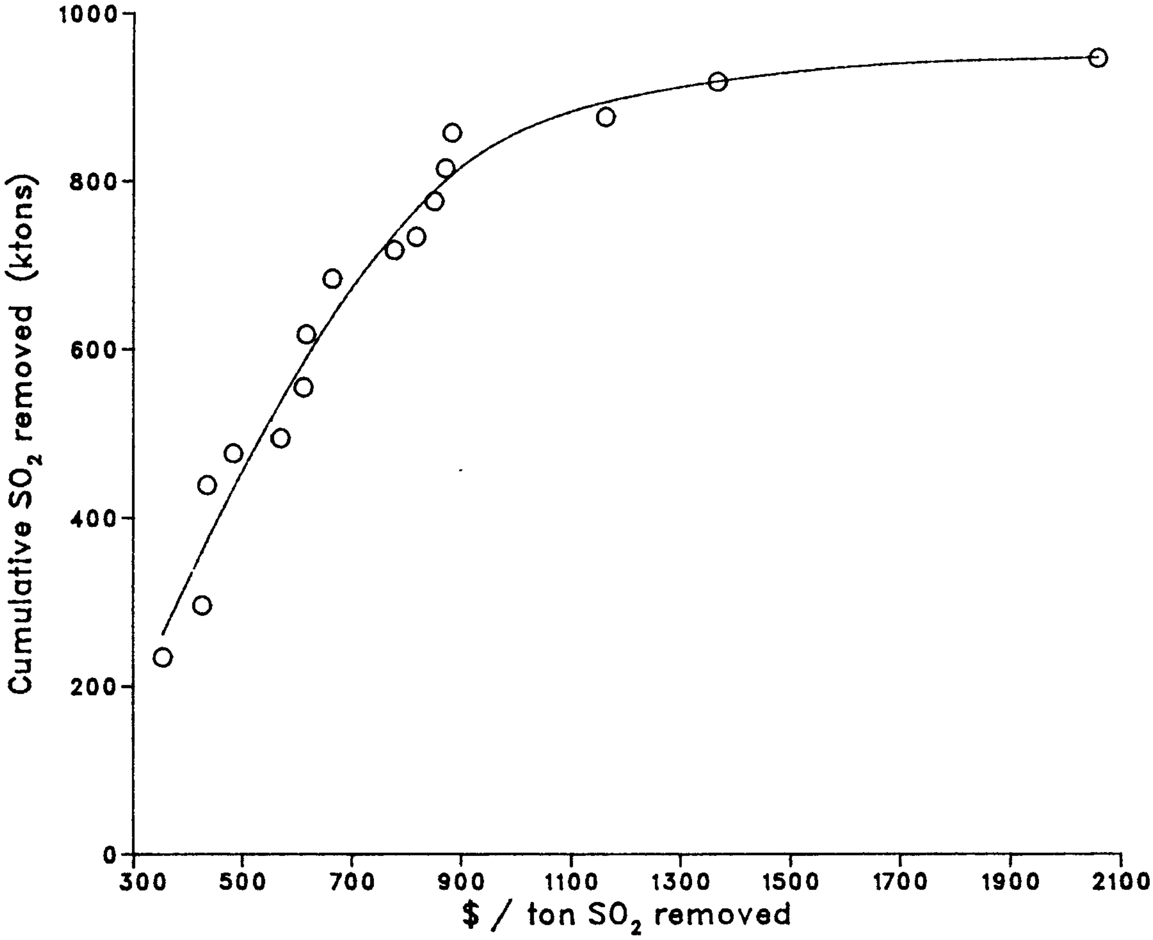


Fig. C.1 Cumulative SO_2 Removal as a Function of Cost (based on firing only the principal coals at the study plants)