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AN INTERPRETATIVE COMPILATION OF EPA STUDIES RELATED TO COAL QUALITY AND CLEANABILITY

by

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ABSTRACT

This report provides an interpretative compilation of the overall EPA coal cleaning effort in the form of indepth analysis, evaluation, and examination of the interrelationships among elements comprising the EPA coal program. The report basically addresses coal (1) washability studies, (2) sulfur reduction by cleaning processes including plant design and associated economics, and (3) the utilization of reject sulfur and coal values from the cleaning processes.

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1.0 INTRODUCTION

The exponential technical and economic growth of the last 25 years has resulted in serious adverse effects on the quality of the Nation's air. A concern for preserving the quality of the environment resulted in the Air Quality Act of 1963 which initiated a concerted effort by federal, state, and local governments for the preservation of the Nation's air quality. This Act called for an expanded federal research and development program and placed special emphasis on the problem of sulfur oxides emissions from the combustion of coal and oil in stationary plants.

Coal provides for 20.5 percent (calendar year 1971) of the total fossil fuel energy consumed by stationary sources (utility, industrial, commercial, and residential). In the utility industry, over 53 percent (calendar year 1971) of the fossil fuel energy requirement is supplied by coal. Of the 33.2 million tons of sulfur oxides emitted into the atmosphere in 1968, 20.1 million tons were from coal-fired utility operations. The ever-increasing demand for electrical energy, the shortage of the available oil-gas reserves, and the delay in the construction and development of breeder-reactor nuclear power plants have resulted and will continue to result in increasing use of coal as a major source of energy for the utility industry. Coal consumption by utilities could reach 500 million tons[1] in 1980 and could be over a billion tons in the year 2000. Because pollution from fuel has long been recognized as a problem, both by EPA and its predecessor organiza-

tions,* major emphasis has been placed on the development of methods for controlling sulfur oxides emissions.

Currently available methods for controlling sulfur oxides emissions from coal-fired stationary combustion sources fall into the following categories:

1. The use of low sulfur coal either naturally occuring or physically cleaned;
2. Chemical treatment to extract sulfur from coal;
3. Removal of sulfur compounds during the combustion process;
4. Removal of sulfur oxides from the combustion flue gas;
5. Conversion of coal to a clean fuel by such processes as gasification and liquefaction.

Of these methods, physical removal of pyritic sulfur (principally FeS_2) is the lowest cost and has the most developed technology.

Sulfur as coal exists in two principal forms, organic and inorganic. The organic sulfur is bound chemically to the coal substance and cannot be physically removed. However, inorganic sulfur (i.e., pyritic) is not bound chemically with the coal substance and may be removed to varying extents by crushing and physical cleaning. The degree of removal is dependent upon pyrite size and distribution, coal size, and other physical characteristics.

*Throughout this report, the acronym "EPA" is used to designate the U.S. Environmental Protection Agency (especially its component organization, the Office of Air Programs), as well as its predecessor agency, the National Air Pollution Control Administration of the Department of Health, Education and Welfare.

Physical cleaning of coal has been used for many years. Its principal purpose has been to reduce the so-called ash-forming impurities. The process in common use for reducing such impurities is a combination of stage crushing and specific gravity separation. Shale and coal having different specific gravities may be separated. Froth flotation, dependent on differences in surface characteristics of coal and coal impurities, is used for removing ash from fine size coal. Existing cleaning processes, while removing impurities from coal, also reduce the total BTU recovery (i.e., a portion of the heat content of the feed will be lost with the refuse). As a result, the BTU content per unit weight of the processed product increases due to removal of low heat value impurities. In practice an economic balance must be achieved between the BTU loss and the improvement in coal quality. This balance may be further influenced by environmental considerations.

In 1965, EPA sponsored a study to quantify the impact that coal cleaning, optimized for pyrite removal, could have on the control of sulfur oxide emissions. This study found that it was impossible to quantify the impact of coal cleaning on sulfur oxide emissions because of large gaps in available information. The study identified the following areas where required information was either not available or was inadequate for appraising this impact:

- Knowledge of the distribution of sulfur forms in (all) major high-sulfur coalbeds in the United States;

- Effectiveness of available commercial coal preparation methods for pyrite separation, together with the development or modification of these techniques to maximize sulfur reduction;
- Identification and assessment of processes that could economically utilize coal cleaning reject material for byproduct recovery, thereby aiding the overall cleaning economics and reducing potential air, water, and solid pollution.

The findings of the 1965 study led EPA to proceed with implementation of a comprehensive program designed to define the potential role of coal cleaning in controlling sulfur oxides emissions from coal-fired sources. The individual program elements were structured to supply the basic information required. The program permitted flexibility for tailoring new program elements in accordance with findings of previous or ongoing studies. An important part of the program was to determine the extent to which the sulfur content of U.S. coals could be reduced by coal cleaning processes based on differences in physical properties. While pyritic sulfur is amenable to removal by such processes, the other major form of sulfur (organic sulfur compounds) is not. A good indicator of the "cleanability" of pyrites from coal is the float-sink, or washability, test in which crushed coal is tested at various gravities to separate the different specific gravity fractions. The coal fractions float and the heavier fractions sink. Such washability tests form an important element of the total program. The overall study concept included the following elements:

- A data base of coal cleanability, containing results of pyrite (and ash) washability studies, to determine the sulfur-release potential of coals from principal utility-coal-producing beds of the United States;
- In-depth studies of existing physical cleaning techniques to obtain maximum pyrite removal;
- The modification of existing methods and evaluation of new methods for sulfur reduction;
- Studies covering pyrite utilization and related economics;
- A feasibility study (with costs) of a prototype cleaning plant to evaluate both economic and technical factors associated with maximizing sulfur reduction;
- A feasibility study with costs of a high-sulfur combustor for utilizing reject material from coal cleaning.

The overall basic program concept (Figure 1) has been to develop a means for achieving full utilization of all values in the coal. The deep-cleaning of coal to maximize sulfur reduction could result in reject material high in coal and sulfur values. This refuse material could be reprocessed into various products: non-polluting refuse for disposal; a pyrite concentrate that could be converted into sulfuric acid; and coal products of various sulfur levels for utilization with flue gas cleaning systems to generate electrical energy. The full utilization of these values could result not only in lower cost fuels, but also in the conservation of the Nation's fossil fuel resources.

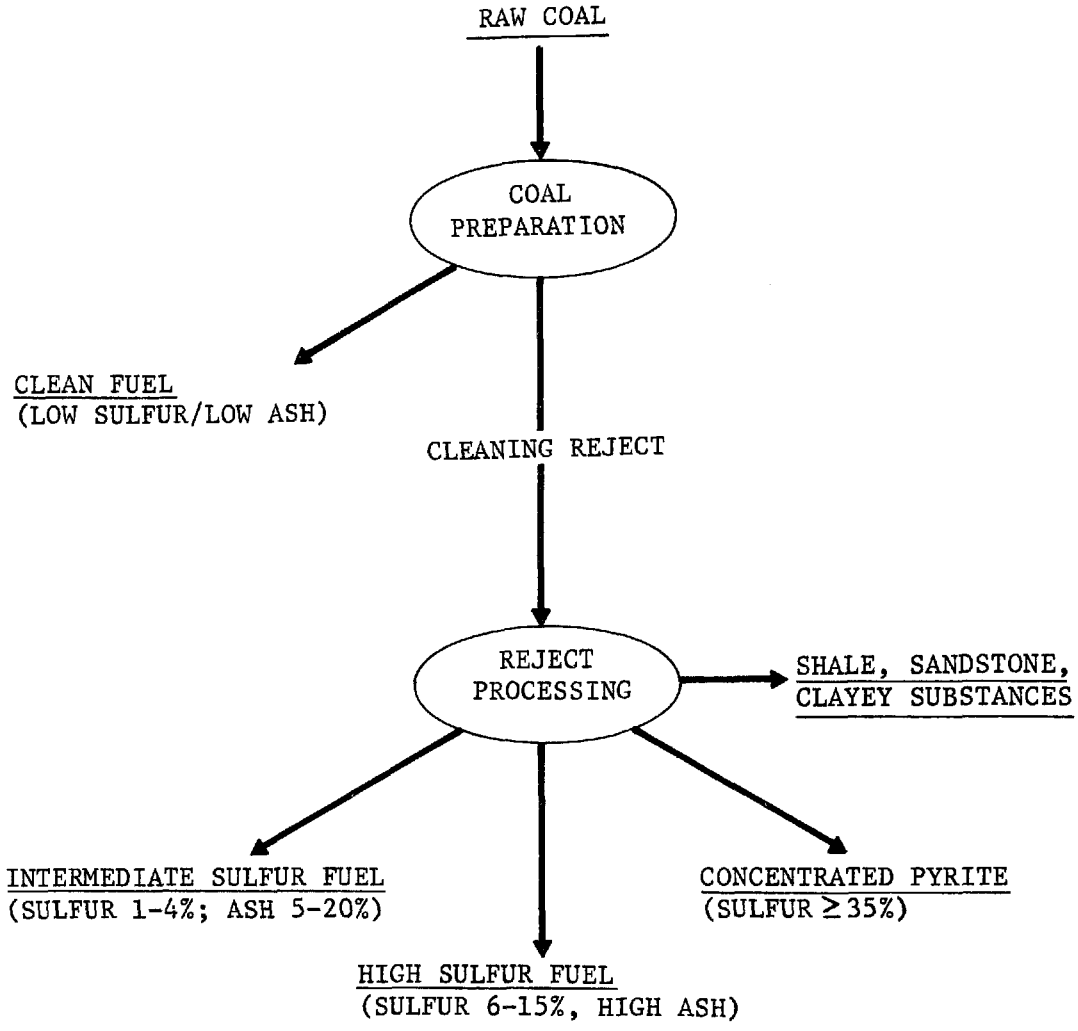


FIGURE 1
FUEL UTILIZATION

A diagram identifying the major elements of the program sponsored by EPA (in whole or part) to develop the information necessary to quantify the potential role of coal cleaning in the control of sulfur oxides emissions and to define the relative attractiveness of cleaning options is given in Figure 2. This figure indicates the interrelations among the various program elements, together with the beginning date for each funded effort and the identification of future efforts required to reach demonstration of commercial applicabilities of considered techniques.

The initial EPA-sponsored washability study began in 1965. Representative samples were collected from mines of major producers of coal primarily for use by the utilities. The samples were stage crushed to three top sizes; coarse - 1½ inch; intermediate - 3/8 inch, and fine - 14 mesh. Washability studies were performed on the various sized fractions with organic liquids of standardized specific gravities to determine the effects of top size and specific gravity parameters upon pyrite liberation and separation.

Because of the the large number of coals to be tested and the need to accelerate their evaluation, EPA expanded the testing program by supporting three additional organizations. The first of these concentrated on regions where preliminary data indicate the presence of coals cleanable for major sulfur reduction.

In another study, EPA cooperatively supported a two-year investigation to evaluate all actively mined coal beds in the state of Illinois, which has the largest bituminous coal reserves in the United States. This effort determined the important physical and chemical properties of

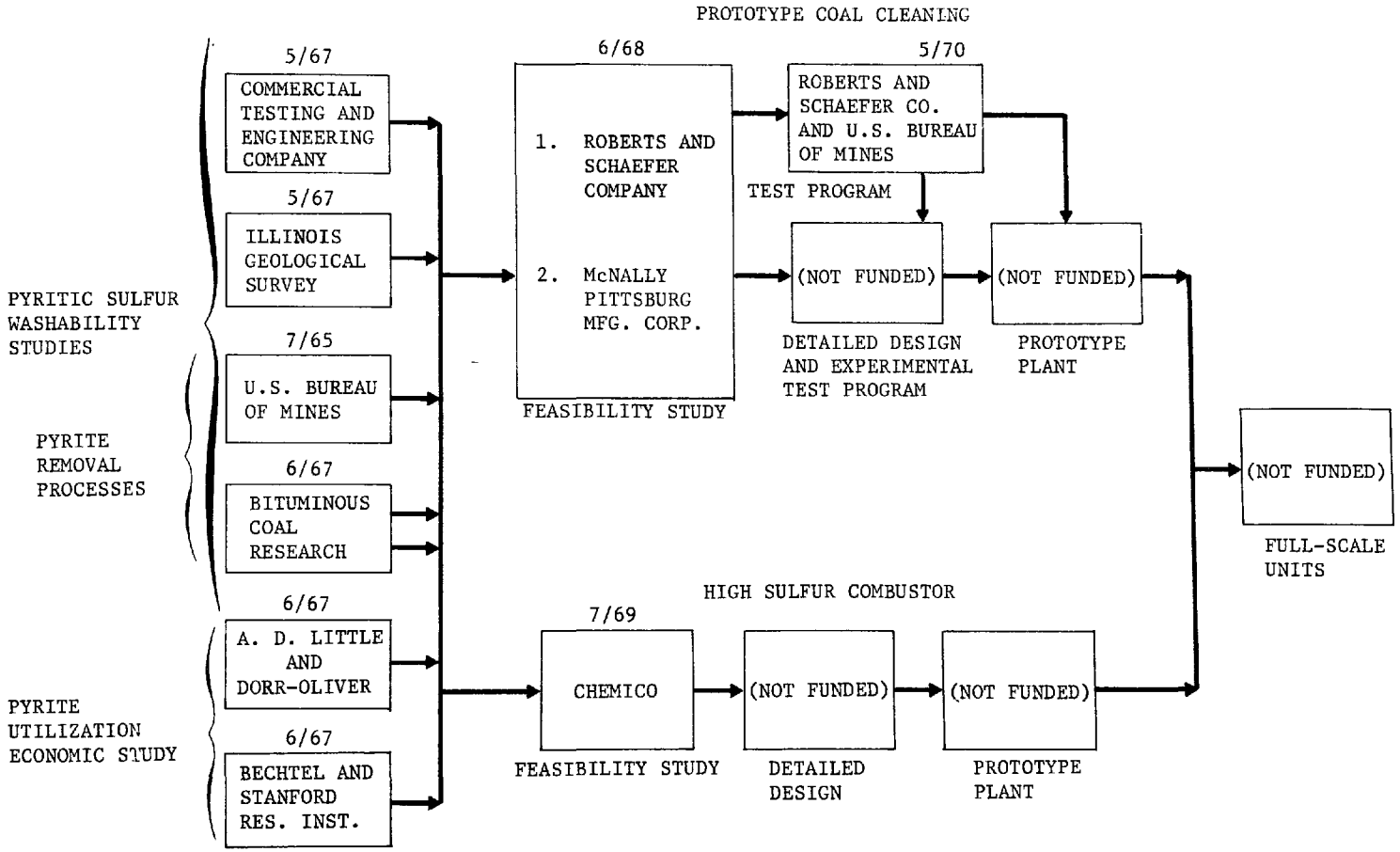


FIGURE 2
PYRITE COAL PROGRAM

Illinois coal, including its washability and distribution of sulfur forms.

To further develop basic data on the effects of size reduction on pyrite liberation, selected samples (in a separate effort) were further reduced in top size to 30 mesh and 60 mesh and evaluated by float-sink evaluation. Although the cleaning of this size material by specific gravity methods is not normal commercial practice, this information would define the maximum effects of size reduction on pyrite liberation and separation.

The four funded washability studies contributed to the development of a substantial body of data on the cleanability of U.S. coals. This information is stored in a computerized data bank to facilitate retrieval, updating, and analysis.

Concurrent with the washability studies, EPA sponsored two separate investigations of techniques for separating and concentrating pyrites from fine coal. One of these evaluated the effectiveness of commercially available equipment; the wet concentrating table, the compound water cyclone, and the concentrating spiral. The other evaluated conventional techniques to define operating parameters, modification of these techniques to maximize sulfur reduction, and the development of new techniques.

In 1967, EPA sponsored two preliminary studies that investigated the economics of recovering by-products from the reject material resulting from coal cleaning. One of these included a review and analysis

of commercially applicable processes for recovering sulfur and the applicability of these processes utilizing coal cleaning refuse. The second was a detailed feasibility study of fluid bed roasting with conversion to sulfuric acid, plus a market analysis for its principal product, commercial grade sulfuric acid. The study findings indicated that the high-sulfur combustor had the highest economic viability potential.

After the preliminary economic studies were completed, EPA funded a feasibility study of a high-sulfur combustor capable of burning the reject material to recover its energy and sulfur values. This study produced an engineering design and cost analysis associated with the utilization of high sulfur reject material to generate power and recover sulfuric acid or elemental sulfur.

In order to determine the scope and cost of conducting investigations and demonstrations of pyrite removal using commercial equipment on a scale approximating commercial capacity, EPA in 1968 funded two independent and competing engineering studies. These efforts, predicated on findings of the washability investigations, were for designing a prototype coal cleaning plant and for estimating capital and operating cost for the plant. Two studies were required to identify the most acceptable design/cost option due to plant and operational complexities.

These various studies are described and their results summarized in the following chapters of this report. The economics, technologies, etc., provided in this report are those of the addressed studies. It

should be noted that since the reported studies were performed conditions have changed and the economic findings and conclusions of the various efforts may not be currently valid.

2.0 SUMMARY

2.1 Introduction

This study provides an interpretative evaluation of the EPA (and its predecessor organizations) coal cleaning program. The EPA coal cleaning effort ostensibly began in 1965 when EPA sponsored a study to quantify the impact that coal cleaning, optimized for pyrite removal, could have on the control of sulfur oxide emissions.[2] This study found that it was impossible to quantify the impact of coal cleaning on sulfur oxide emissions due to large gaps in available information.

The findings of the 1965 study led to the establishment of a comprehensive program designed to define the potential role of coal cleaning in controlling sulfur oxide emissions from coal-fired sources. Principal elements of the resulting program were:

- A data base of coal cleanability, based on findings of pyrite washability studies, to determine the sulfur-release potential of coals from principal utility coal producing beds of the United States;
- An in-depth study of pyrite removal processes;
- Studies covering pyrite utilization and related economics;
- Feasibility studies of a prototype cleaning plant to evaluate the economic and technical factors associated with maximizing sulfur reduction;
- A feasibility study of a high-sulfur combustor for utilizing reject material from coal cleaning.

In essence, the overall program concept was to develop methods for achieving utilization of all values in the coal. The deep cleaning of coal to maximize sulfur reduction could result in a reject material high in coal and sulfur values. This refuse (reject) material could be processed into various products: non-polluting refuse for disposal; a pyrite concentrate that could be converted into sulfuric acid; and coal products of various sulfur levels for utilizing with flue gas cleaning systems to generate electrical energy.

The principal elements that comprized the EPA program are summarized below.

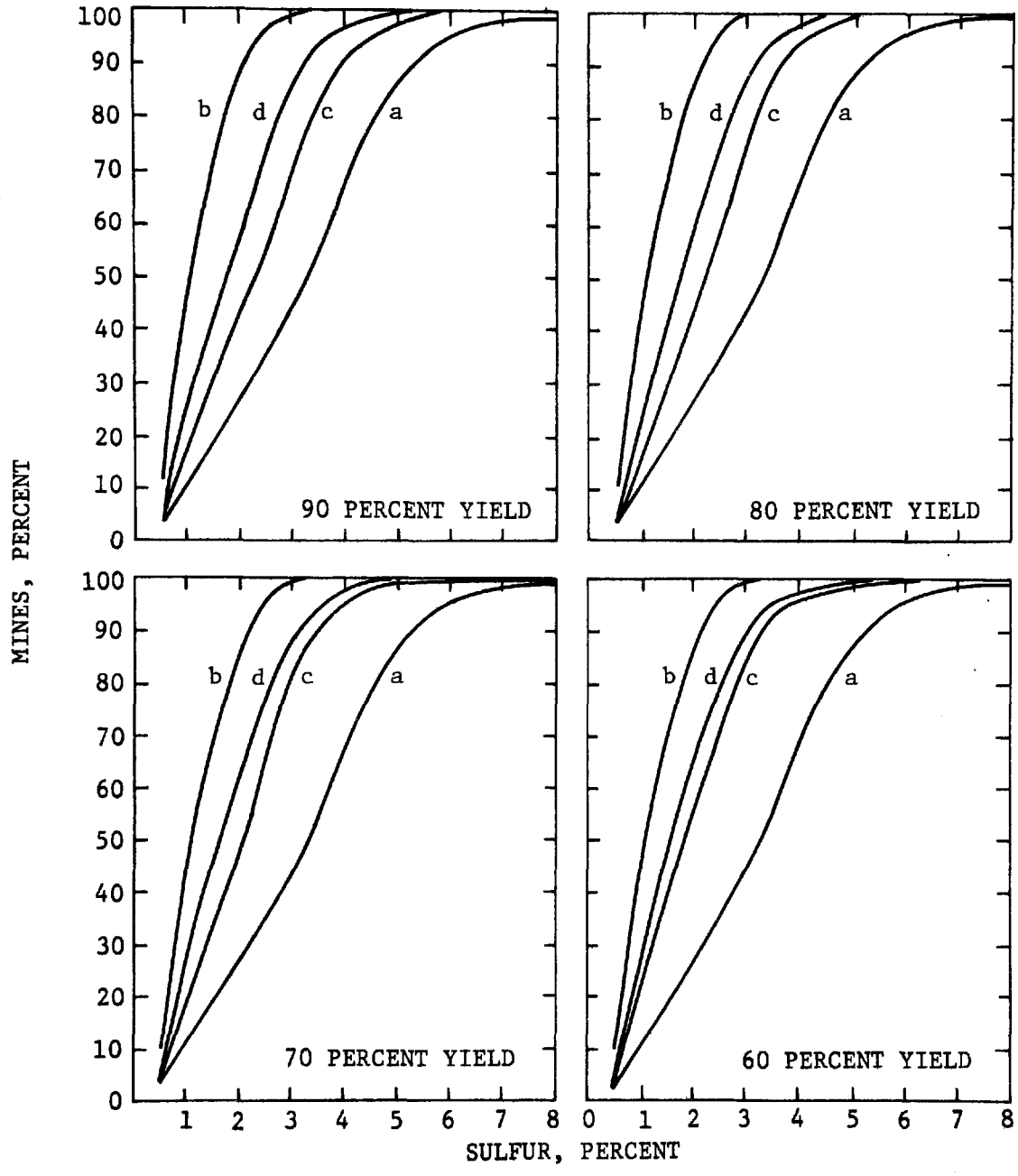
2.2 Washability Studies

Sulfur is found in raw coal in two major forms: organic and inorganic (pyritic) sulfur. Organic sulfur is chemically bound to the organic structure of the coal and cannot be removed by use of conventional washing methods. The pyritic sulfur occurs in particles of varying size mixed with the coal. By crushing (to liberate the pyritic sulfur) and washing (to remove the liberated particles), the total amount of sulfur in the coal may be reduced. The degree of removal of the pyritic sulfur is dependent on the size of the particles of pyrites; the finer the particles, the more difficult to remove by washing. The total sulfur reduction, therefore, is dependent on the amount of organic sulfur and the effects of crushing to liberate the pyritic sulfur. The desulfurization process results (as do most beneficiation processes) in some loss in total heat content of the processed coal.

A summary of 322 washability tests reported by the Bureau of Mines shows that the organic sulfur and the effects of crushing (Figures 3 and 4) vary widely, as would be expected, when washability data of coals throughout the United States are combined.

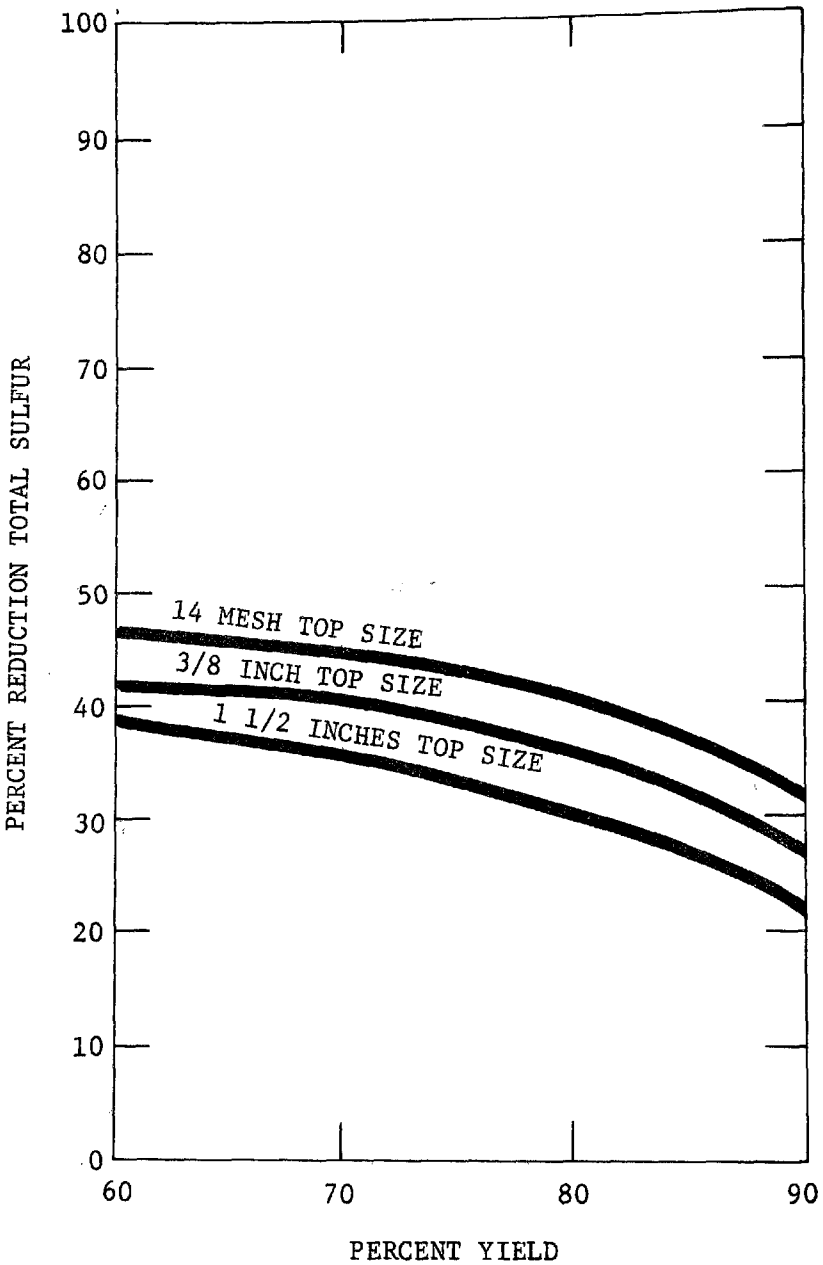
The average total sulfur content of all coal studied in the Bureau of Mines reported investigation of coal washability is 3.23 percent at a raw coal top size of 3/8 inch (Figure 5). When washed to a 90 percent yield, this average was reduced to 1.95 percent; reducing the yield to 60 percent results in a 1.82 percent average value. Figure 6 shows the average pyritic sulfur content of the raw coal is 2.05 percent. At 90 percent yield this average was reduced to 0.75 percent; at 60 percent yield it was reduced to 0.51 percent. On the average, regardless of yield, the organic sulfur content of the coals was 1.2 percent. The average percent total sulfur reduction and the average percent pyritic sulfur reduction at the varied yields are shown in Figures 7 and 8. Figure 3 shows that at a 60 percent yield only 20 to 25 percent of the coals sampled could produce a one percent or less total sulfur washed coal.

The production of one percent or less total sulfur coal by means of physical cleaning is governed by the amount of organic sulfur and particle sizes of the pyrite in the coals (the fine, intimately mixed pyrite particles are impossible to remove by conventional washing processes), regardless of cost. In general, the lower the level of total sulfur required in the washed coal, the higher the cost of cleaning due to the lower recovery of the washed coal (i.e., greater loss of coal values during washing).



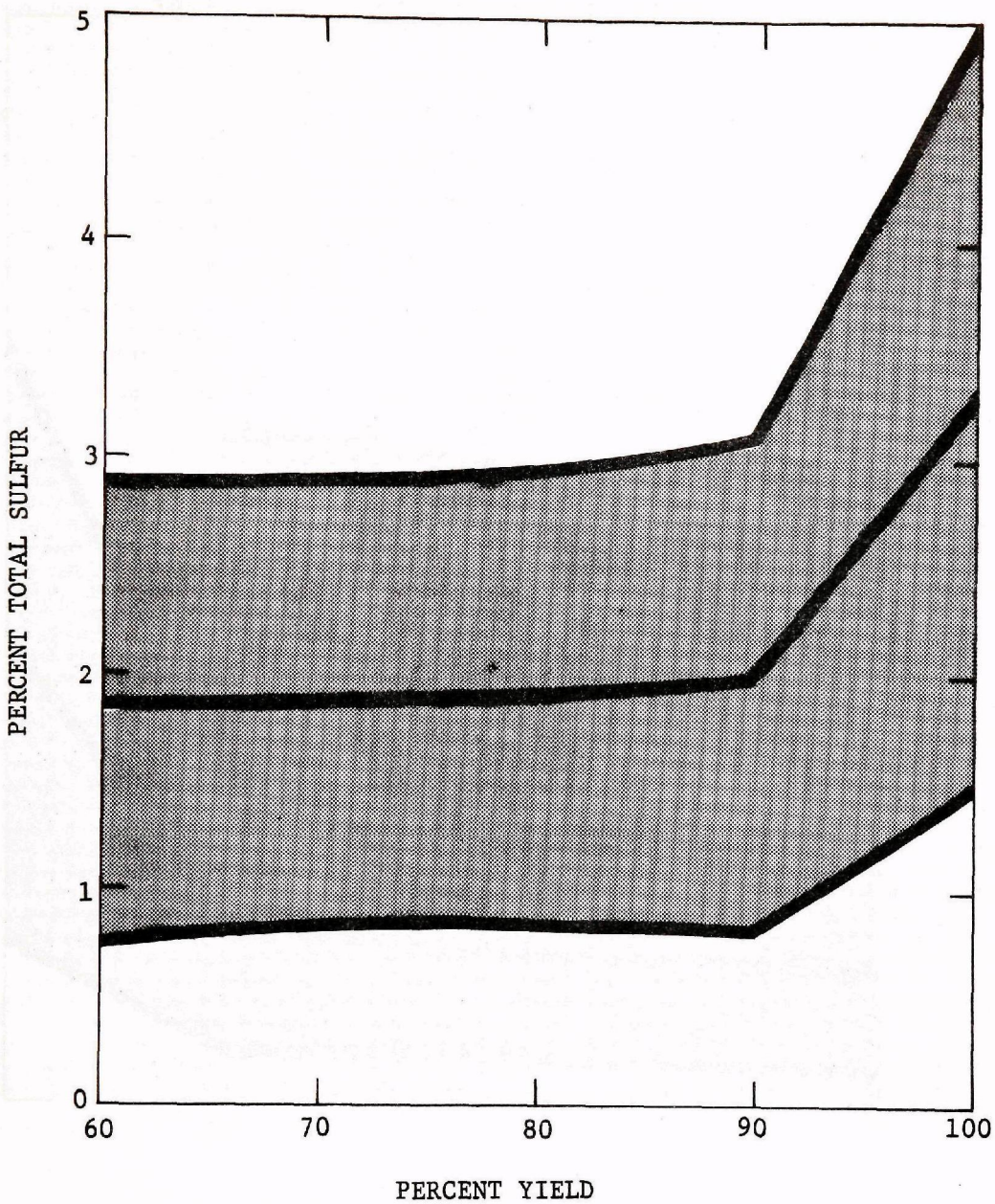
(a) RAW COAL TOTAL SULFUR CONTENT CURVE; SOURCE: REFERENCE 8
(b) RAW COAL ORGANIC SULFUR CONTENT CURVE;
(c) WASHED COAL TOTAL SULFUR CONTENT COAL CURVE WHEN RAW COAL WAS CRUSHED TO MINUS 1½ INCHES; AND,
(d) WHEN RAW COAL WAS CRUSHED TO MINUS 14 MESH.

FIGURE 3
WASHABILITY SUMMARY OF ALL COALS



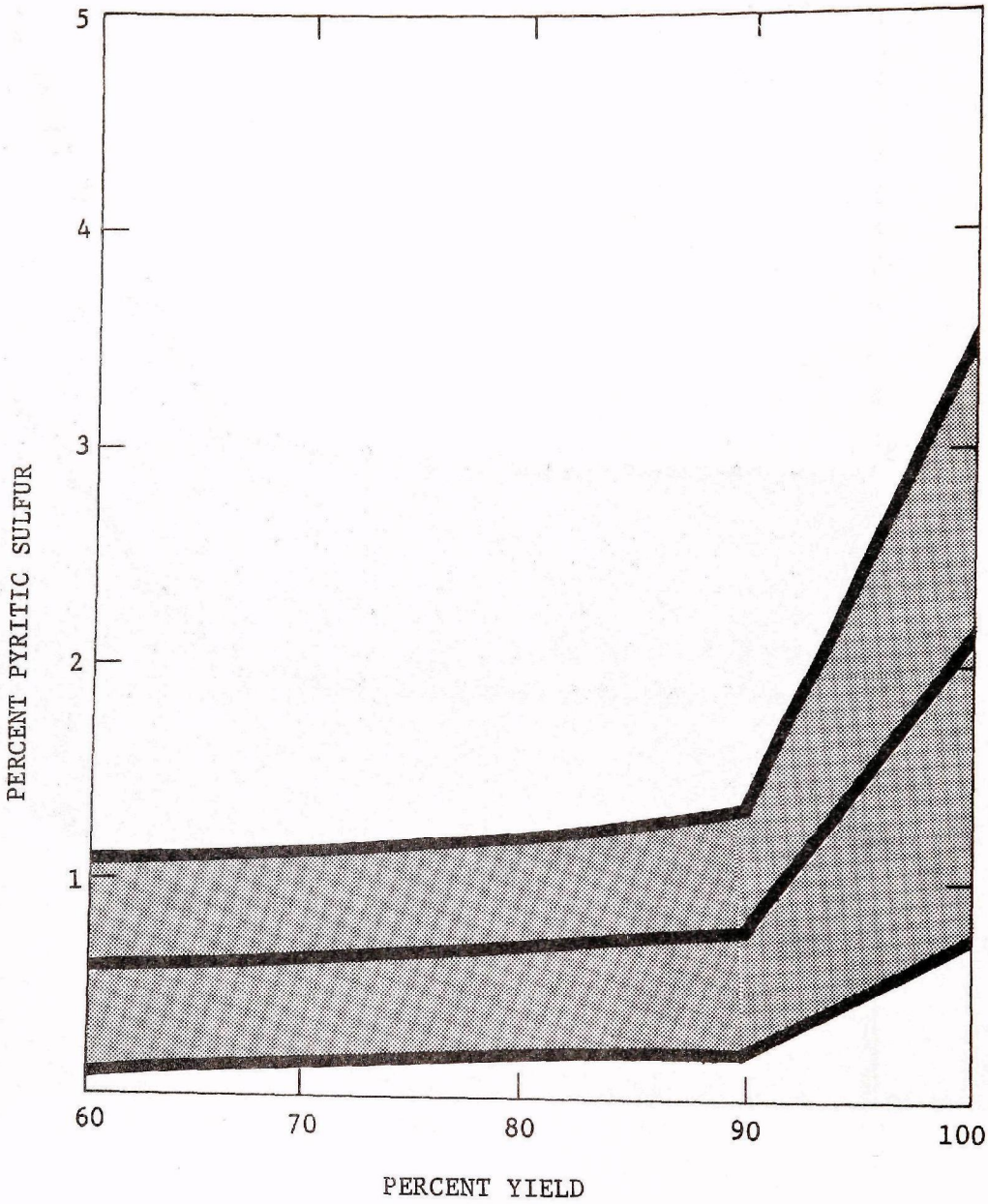
SOURCE: REFERENCE 8

FIGURE 4
EFFECT OF CRUSHING ON LIBERATION OF TOTAL SULFUR, SUMMARY OF ALL COALS



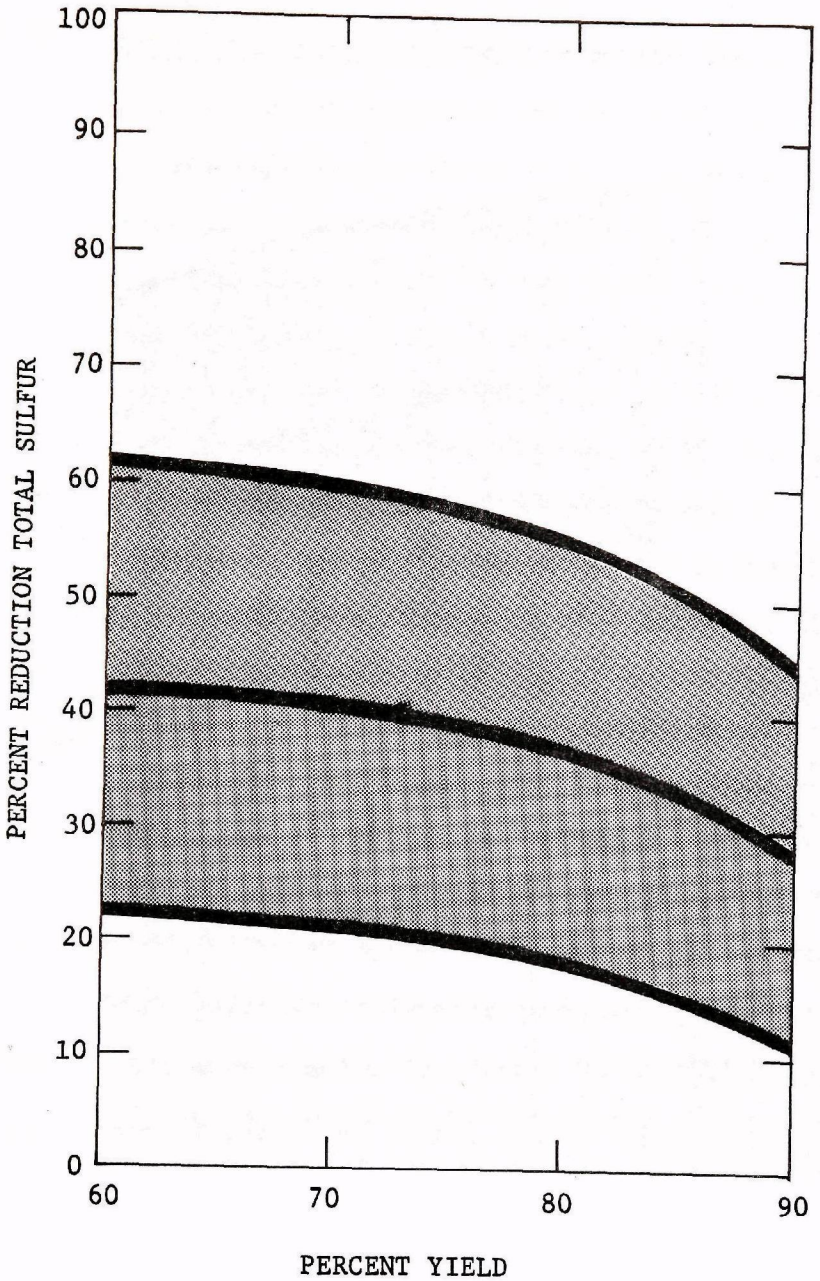
SOURCE: REFERENCE 8

FIGURE 5
AVERAGE TOTAL SULFUR CONTENT, ±1 STANDARD DEVIATION AT 3/8 INCH TOP SIZE, SUMMARY OF ALL COALS



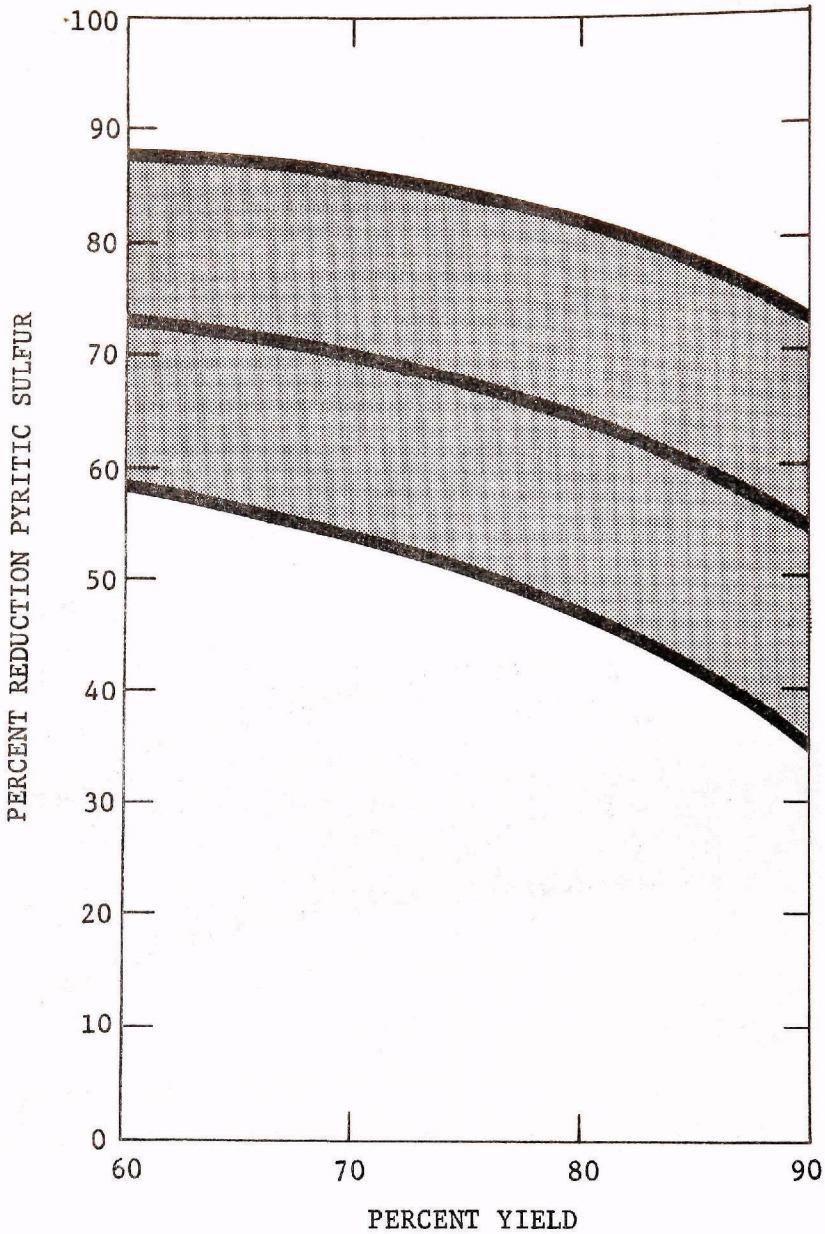
SOURCE: REFERENCE 8

FIGURE 6
AVERAGE PYRITIC SULFUR CONTENT, ±1 STANDARD DEVIATION
AT 3/8 INCH TOP SIZE, SUMMARY OF ALL COALS



SOURCE: REFERENCE 8

FIGURE 7
AVERAGE PERCENT TOTAL SULFUR REDUCTION ±1 STANDARD DEVIATION AT 3/8 INCH TOP SIZE, SUMMARY OF ALL COALS



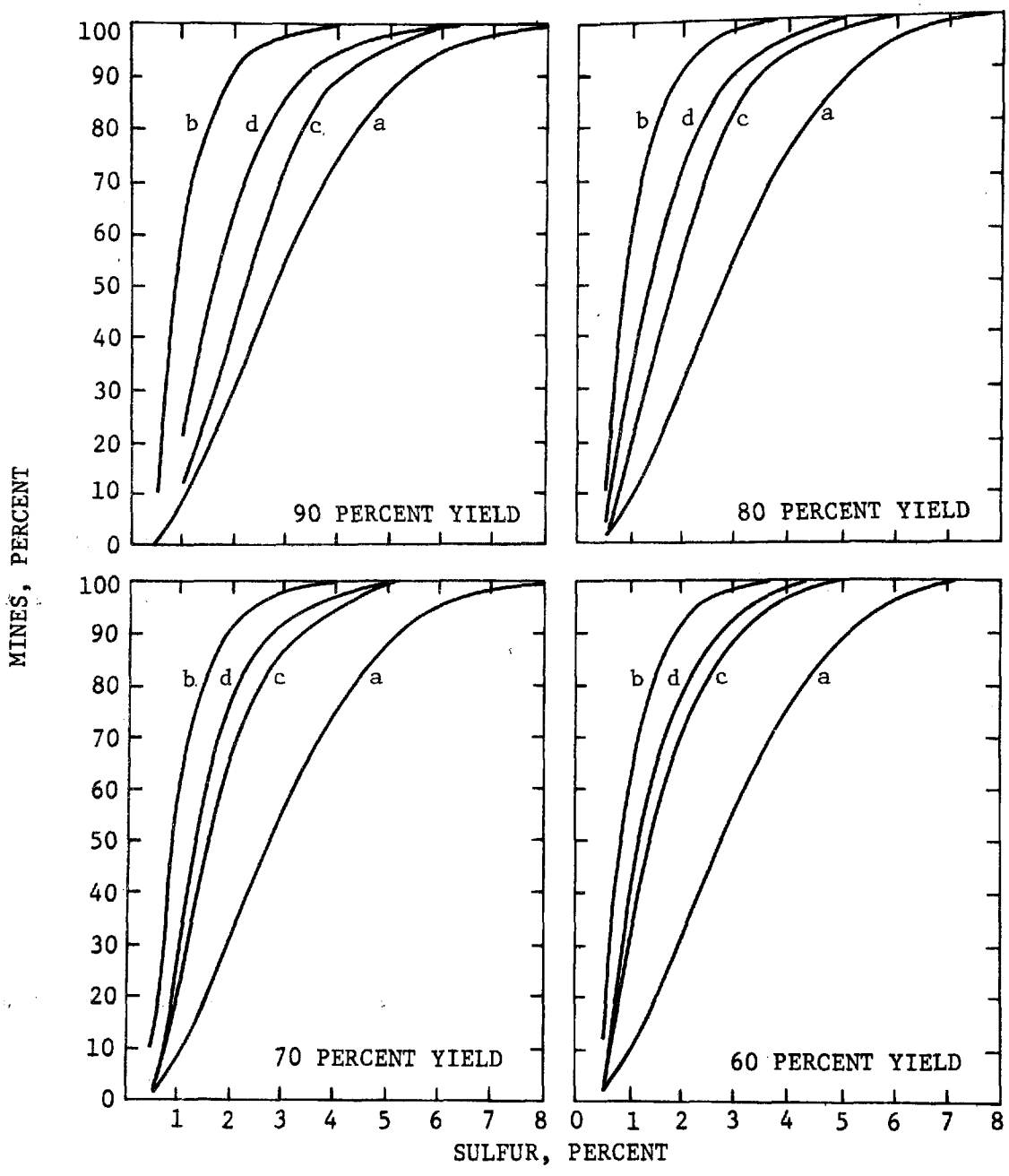
SOURCE: REFERENCE 8

FIGURE 8
AVERAGE PERCENT PYRITIC SULFUR REDUCTION, ±1 STANDARD DEVIATION AT 3/8 INCH TOP SIZE, SUMMARY OF ALL COALS

The three regions indicating a potential for washing to a total sulfur content of one percent or less are the Northern Appalachian (Figure 9), the Southern Appalachian (Figure 10), and Eastern Interior or Midwest Region (Figure 11). The remaining coal producing regions given less attention or excluded are: the Western Interior (the coals in this region are characteristically high in sulfur content regardless of the physical treatment used) and Northern and Southern Rocky Mountain (these coals are generally of low sulfur content).

As shown by Figures 4 and 5, coal crushed to 3/8-inch top size and cleaned to yield in the order of 90 percent will provide the predominant benefit. The figures show that, on the average, sulfur content will decrease by less than ten percent with an additional yield sacrifice of 30 percent (i.e., 90 to 60 percent). Even so, it must be emphasized that individual cases may vary and must be independently assessed.

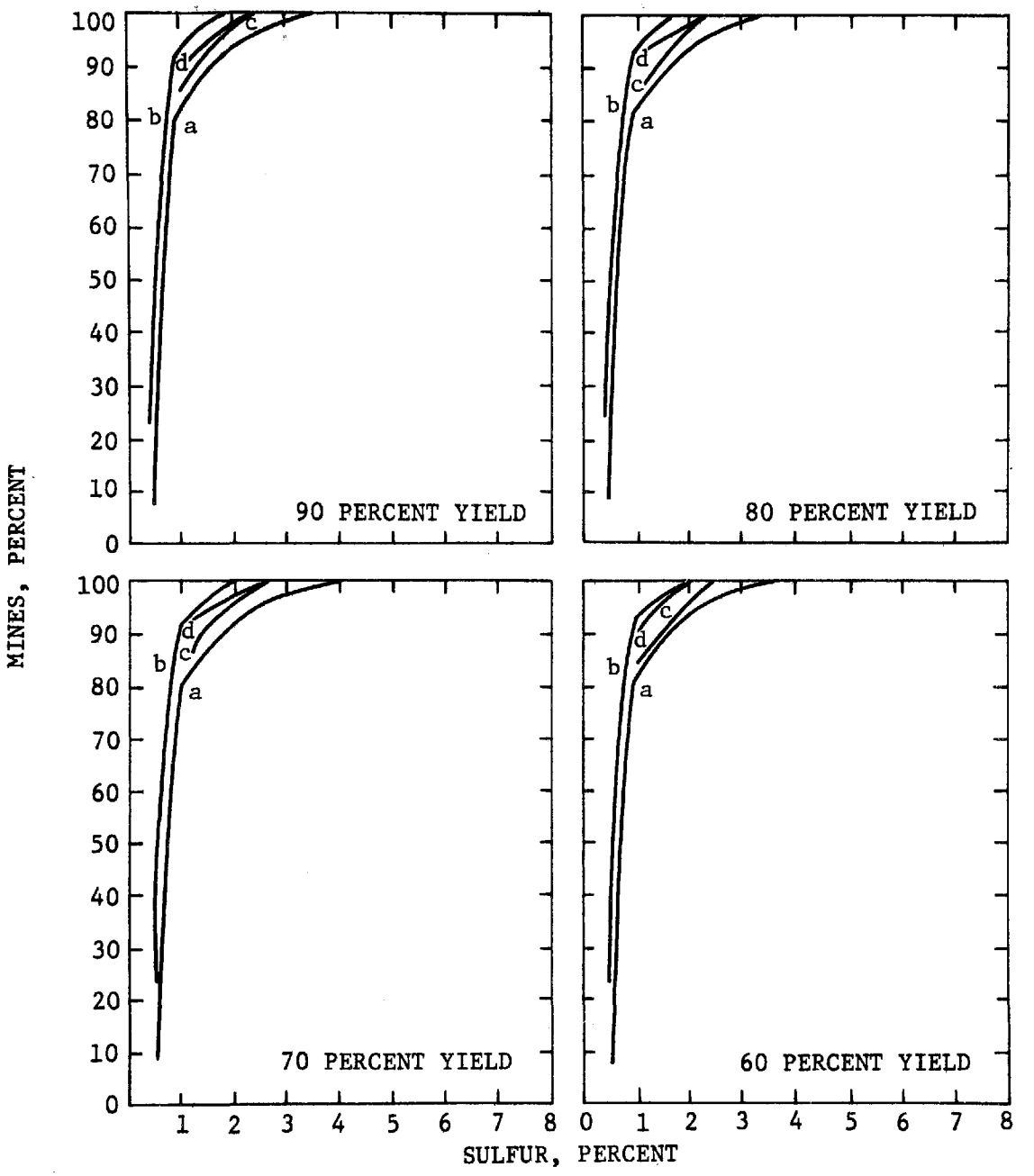
In addition to the Bureau of Mines reported washability studies, 67 washability tests on Illinois coals were reported by the Illinois Geological Survey. The test samples were taken from Illinois coal mines located in significant mining areas in the state. The Illinois Geological Survey tests indicated that most Illinois coals have 3 to 5 percent total sulfur and only in those coals having a relatively low-sulfur content as mined could the total sulfur content be reduced to 1.5 percent or less by washing techniques. Of the 67 coal samples tested, 6 could be washed to a total sulfur level of 1 percent and 10 could be washed to 1.5 percent with an 80 percent minimum recovery.



(a) RAW COAL TOTAL SULFUR CONTENT CURVE;
(b) RAW COAL ORGANIC SULFUR CONTENT CURVE;
(c) WASHED COAL TOTAL SULFUR CONTENT COAL CURVE WHEN RAW COAL WAS CRUSHED TO MINUS 1½ INCHES; AND,
(d) WHEN RAW COAL WAS CRUSHED TO MINUS 14 MESH.

SOURCE: REFERENCE 8

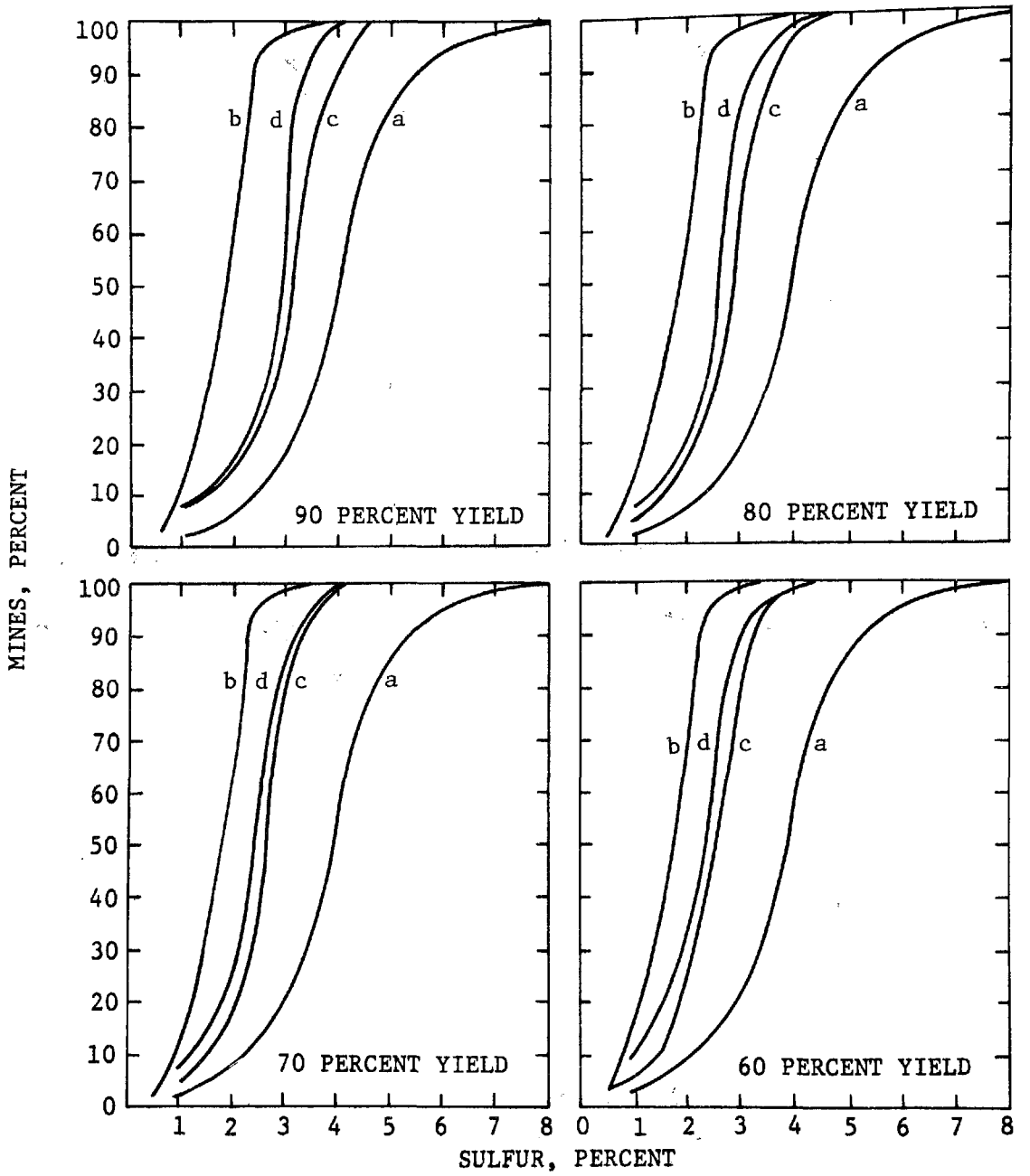
FIGURE 9
WASHABILITY OF NORTHERN APPALACHIAN REGION COALS



(a) RAW COAL TOTAL SULFUR CONTENT CURVE;
(b) RAW COAL ORGANIC SULFUR CONTENT CURVE;
(c) WASHED COAL TOTAL SULFUR CONTENT COAL CURVE WHEN RAW COAL WAS CRUSHED TO MINUS 1½ INCHES; AND,
(d) WHEN RAW COAL WAS CRUSHED TO MINUS 14 MESH.

SOURCE: REFERENCE 8

FIGURE 10
WASHABILITY OF SOUTHERN APPALACHIAN REGION COALS



(a) RAW COAL TOTAL SULFUR CONTENT CURVE;
(b) RAW COAL ORGANIC SULFUR CONTENT CURVE;
(c) WASHED COAL TOTAL SULFUR CONTENT COAL CURVE WHEN RAW COAL WAS CRUSHED TO MINUS 1½ INCHES; AND,
(d) WHEN RAW COAL WAS CRUSHED TO MINUS 14 MESH.

SOURCE: REFERENCE 8

FIGURE 11
WASHABILITY OF MIDWEST REGION COALS

2.3 Laboratory and Pilot Studies Evaluating Processes For Pyrite Removal From Fine Coals

The goals of EPA-sponsored laboratory and pilot study projects conducted by the Bureau of Mines and Bituminous Coal Research, Incorporated were:

1) to determine the operating parameters for maximum pyrite separation,
2) to modify existing techniques and/or develop new techniques to separate pyrite from fine coal, and
3) to evaluate methods to process coal cleaning rejects so as to concentrate the pyrite and reclaim clean coal products.

The Bureau of Mines concentrated on equipment operational parameters and the development of new techniques while the Bituminous Coal Research effort concentrated on the applicability of equipment to various coals. The following equipment or processes were evaluated by the two contractor organizations.

EQUIPMENT/PROCESS	INVESTIGATED BY	
	BUREAU OF MINES	BITUMINOUS COAL RESEARCH, INC.
Wet Concentrating Table (Deister)	X	X
Concentrating Spiral (Humphrey)	X	X
Hydrocyclones	X	X

EQUIPMENT/PROCESS	INVESTIGATED BY BUREAU OF MINES	INVESTIGATED BY BITUMINOUS COAL RESEARCH, INC.
Air Classifiers		X
Electrokinetic Techniques	Y	
Agglomo-Separation	X,Y	
Froth Flotation	X,Y	

X - designates pilot plant tests

Y - designates laboratory-scale tests

2.3.1 Principal Findings

Wet Concentrating Table

In tests, the wet concentrating table proved effective in removing free pyrite from coal. Coals with a high proportion of pyritic sulfur relative to organic sulfur are particularly amenable to sulfur reduction by this process. Two-stage cleaning tests, in which a coarse sample was tabled and the clean fraction pulverized and retabled, indicated that pyrite removal can be enhanced by use of the concentrating table in two stages.

Concentrating Spiral

The concentrating spiral experienced a rapid deterioration of washing efficiency with feed size below 35 mesh, this being a normal characteristic of specific gravity separators.

Overall, the excellent results the concentrating spiral provided on fine-size coal suggest that it should be considered as a "rougher" cleaning unit to remove pyrite from high sulfur coals prior to flotation.

Double-stage cleaning indicate that for some coals the spiral process produces similar reductions and yields to those obtained with the wet concentrating table.

Water-Only Cyclone

Preliminary results of the Bureau of Mines water cyclone performance evaluation tests showed excellent pyritic sulfur reductions were obtainable. The clean coal recoveries were highly dependent on the size of the material. Clean coal recovery of plus 48 mesh material was low while most of the minus 100 mesh material reported to the clean coal product.

Water cyclone tests were also conducted by Bituminous Coal Research, Inc. (BCR, Inc.). Feed coals were pulverized to minus 30 mesh prior to test runs. BCR, Inc., results indicated that in general the compound water cyclone provided smaller sulfur reductions than were achieved by the concentrating table. However, BCR, Inc., believes that improved results in total sulfur reduction could be obtained by using a closer-sized feed to the water cyclone.

Air Classifier

Air is used to separate relatively coarse grind of pulverized coal into a fine fraction and a coarse, pyrite rich fraction using the BCR-Majac and Alpine zigzag air classifiers. Pyrite could then be removed from coarse fractions by wet-coal preparation techniques.

The reduction of total sulfur through use of the Majac unit ranged from 20.1 to 51.7 percent for 10 samples. Only one coal was processed on the Alpine zigzag unit.

Electrokinetics

The electrokinetic process for the physical cleaning of coal uses the technique of electrophoresis for separating the pyrite from the coal. The laboratory-scale investigation indicated that pyrite and other impurities such as silica could be separated from the coal. The technique, unfortunately, was deemed uneconomical for scaling up to the pilot stage as a coal cleaning procedure.

Agglomo-Separation (Oil)

An oil agglomeration process for the recovery of clean coal from slime size material and the sulfur and ash reduction potential of this process was investigated by the Bureau of Mines. This process provided negligible reduction in sulfur; however, the reduction in coal ash content was good.

Froth Flotation

Froth flotation is a process for separating fine-size particles by selective attachment of air bubbles to coal particles, causing the coal to be buoyed up into a froth while leaving the refuse particles in the water. Of the several innovative processes for pyrite separation investigated under the EPA Clean Coal Program, the froth flotation technique appears to show the greatest potential for scale-up to commercial operation.

Concentration of Pyrite from Refuse

Studies were performed to determine the potential of fine-cleaning techniques for preparing a concentrated grade of pyrite from coal cleaning reject material. Coals from six mines were cleaned and the reject concentrated by staged separation with a wet concentrating table and a hydraulic classifier. The results indicate that pyrite concentrates with sufficiently high total sulfur content for conventional acid-making processes were achieved for all coals tested, sometimes at the expense of percentage of sulfur recovered. Total sulfur in the pyrite concentrates ranged from 35.6 to 48.6 percent.

2.4 Prototype Coal Cleaning Plant

The washability studies and pilot plant investigations indicated the amenability of a wide range of coals to physical desulfurization under carefully controlled conditions. Although testing for pyrite removal could be conducted to a limited degree in some existing preparation plants, the equipment and cleaning circuits of such plants are not normally arranged to maximize sulfur reduction but to meet ash and BTU specifications. Ideally, a plant to be used for investigating and demonstrating desulfurization methods at high through-put capacities would provide flexibility of equipment configurations, cleaning circuits, and operating conditions.

In order to determine the scope and cost of conducting investigations and demonstrations of pyrite removal using commercial cleaning

equipment on a scale approximating commercial capacity, EPA funded two independent and competitive studies for designing a prototype coal cleaning plant of 50-100 tons per hour capacity and for estimating the capital and operating cost for the plant. The study objectives were to produce a prototype plant design, together with cost estimates for building, equipping and operating a plant capable of reducing the sulfur of coals having widely variable washability characteristics.

The prototype plant design and cost studies were conducted by the McNally Pittsburg Manufacturing Corporation and the Roberts and Schaefer Company of Chicago. The major difference in the two studies was plant design; Roberts and Schaefer's design was the more complex of the two; however, it offered the most flexibility.

The Roberts and Schaefer cost estimate for a fifty-two month program covering plant cost, operating cost, laboratory services, and contractor's fee came to $16,457,965. In addition, a cost estimate was provided for a modified, alternate, lower price program that would not unduly sacrifice program objectives. The cost estimate for the alternate forty-four month program (instead of the fifty-two month basic program) amounted to $8,923,200.

The McNally Pittsburg cost estimate for a fifty-four month program covering plant cost and operating cost, which include laboratory services, amounted to $11,406,775. Even though not specifically stated, it is assumed that the contractor's fee charge is included in the above amount.

2.5 Pyrite Utilization Economic Studies

The purposes of the Pyrite Utilization Economic Study portion of EPA's overall pyrite coal program are:

1. To investigate the economics of utilizing the pyrites obtained from coal beneficiation;
2. To evaluate the applicability of alternative commercial processes for recovering energy and chemical values from coal cleaning reject material; and
3. To design, construct, and operate a plant that would demonstrate the technical and economic feasibility of the processes.

Investigations concerned with the first two purposes were conducted concurrently. In 1967, EPA contracted with the Bechtel Corporation to perform a general review and evaluation of costs and technology of other available processes for pyrite-coal utilization. Also in 1967, a contract was awarded to A. D. Little, Inc. (assisted by Dorr-Oliver) to determine the costs and benefits associated with the processing of pyrite removed from coal. This study effort was concentrated on the technology and economics of fluidized-bed roasting of pyrite-coal followed by conversion of sulfur dioxide to sulfuric acid by the contact process. On the basis of the resulting technical and economic data, EPA decided to look more closely at a system for burning the high-sulfur, high-ash material produced by coal desulfurization. The resulting effort was performed by the Chemical Construction Company (Chemico); a summary is presented in Section 2.5.3.

2.5.1 The Bechtel Corporation Study

Eight processes were selected by the Bechtel Corporation for investigating the recovery of chemical and energy values from pyrite-coal refuse. After initial study, two of the eight processes were selected for analysis at a more detailed level. The selected processes were the "Combustion/Sulfur-Oxides-Removal Process" and the "Fluidized-Bed Pyrite Roasting Process". These two, in the order listed, had the most favorable economics. The overall economics of the "Combustion/Sulfur-Oxides-Removal Process" indicated the possibility of an economic benefit while the "Fluidized-Bed Pyrite Roasting Process" indicated the likelihood of a small cost penalty. The study was predicated on a maximum sulfur level of washed coal of 1.0 percent and coal washing refuse containing from about 4 to 25 percent sulfur and ash levels of 20 to 90 percent.

The Bechtel findings are based on examining two general classes of processes for utilizing coal refuse. These are:

1. The feed is the entire refuse stream from coal preparation, and
2. A concentrated feed is used.

The study (at time of performance) indicated that:

1. None of the processes which use the entire refuse stream has reached commercial status,
2. Processes which feed a pyrite concentrate are commercial but have not been operated with pyrite-coal mixtures, and

3. The Combustion/Sulfur-Oxides-Removal Process shows the most favorable economic outlook and its technology appears sound. The Monsanto process for removing sulfur oxides from flue gas was selected for the economic estimates because of its advanced development state and simplicity.

For the study, a method was developed to calculate the value of coal refuse as a function of numerous variables. The method assumes that coal refuse is bought jointly by the owners of a closely integrated electric utility and sulfuric acid plant; wherein each of the two investors would pay for his share of the refuse value (fuel or sulfur). The owner of the coal preparation plant could use this income to offset part or all the cost of coal cleaning. Table I shows the results of an estimate for values of the two refuse compositions for specific assumptions.

The study indicated that refuse value depends on many variables, the most important being refuse power plant capital cost and sulfuric acid sales price. Other factors affecting refuse values are:

- Refuse ash concentration,
- Refuse power plant operating and maintenance cost,
- Sulfuric acid recovery plant investment, and
- Rate of return on acid recovery plant.

2.5.2 The A. D. Little Study

As previously indicated, the A. D. Little effort was predicated on

TABLE I

VALUE OF REFUSE

REFUSE SULFUR CONCENT. (PERCENT)	SULFURIC ACID PRICE ($/TON)	NET REFUSE ENERGY VALUE (CENTS/ 10^6 BTU)	NET REFUSE SULFUR VALUE ($/TON SULFUR)	TOTAL REFUSE VALUE		CHANGE IN COAL PREP. COST (PERCENT)
				($/TON REFUSE)	(CENTS/ 10^6 BTU)	
6.38	10.00	4.0	-10.24	-0.06	nil	2.5 increase
6.38	15.00	4.0	7.70	1.09	7.3	45.4 decrease
10.62	10.00	4.0	7.18	1.35	9.2	56.2 decrease
10.62	15.00	4.0	25.10	3.25	22.2	135.4 decrease

ASSUMPTIONS

Refuse Power Plant Capacity	300 Mw (net)
Refuse Power Plant Capital Cost*	170 $/kw
Return On Book Value	8.0 percent
Refuse Ash Concentration	34.0 percent
Refuse Moisture	15.0 percent
Sulfur Oxides Recovery Plant Investment (in terms of refuse power plant capacity)	42 $/kw
Discounted Rate of Return	12.5 percent
Coal Preparation Plant Yield	80 percent
Coal Preparation Cost	$0.60/ton clean coal

*Does not include cost for SO_2 recovery plant.

fluid-bed roasting of pyrite-coal followed by conversion of sulfur dioxide to sulfuric acid by the contact process. The study found that the economic feasibility of the process, i.e., the amount that can be paid for pyrite feed (coal cleaning reject), depends on a number of interrelated factors including: the price of elemental sulfur and sulfuric acid, the location of the acid plant relative to pyrite deposits, the expected return on investment, and the markets for sulfuric acid. Taking these and other considerations (including an f.o.b. price for elemental sulfur of $38 per long ton) into account, it was estimated that the net financial benefit to coal operators for producing low-sulfur (1 percent or less) coal and an acceptable pyrite feed material could range from $1.16 to $1.57 per ton of coal processed. The results are based on the following:

- It is reasonable to expect that a premium of $1.10 to $1.20 per ton of coal should be obtained by mines supplying less than 1 percent sulfur coal to utilities subject to stringent air pollution abatement restrictions;
- Coal companies should obtain a benefit of approximately $0.15 per ton of coal processes resulting from reduced disposal requirements and reduced air and water pollution.

In order to support a 1500 ton per day sulfuric acid plant (the minimum size believed suitable for economic manufacture), considerable tonnages of pyrite-bearing coal must be processed. The amount required would probably come from more than one mine.

Costs associated with the manufacture of sulfuric acid from a pyrite feed will vary primarily as a function of three major variables: plant size, plant type, and feed composition. Plant size and type will be determined to a considerable degree by market conditions projected over plant life. Even so, feed stream characteristics could change in accordance with raw material resources and beneficiation processes.

For the study a broad range of possible pyrite feed compositions were arbitrarily selected and evaluated. The pyrite feed composition has a pronounced effect on almost all of the process requirements in both the pyrite roasting section and the contact acid section. While the cost of pyrite-coal beneficiation must ultimately be taken into account, for practical purposes a feed composition of no worse than 70 percent pyrite, 10 percent coal, and 20 percent gangue was assumed for acid manufacture. For the study a feed of 85 percent pyrite, 10 percent coal, and 5 percent inerts was used.

On the basis of the three major parameters -- plant capacity, feed composition, and plant type -- investment and operating costs were calculated for each possible combination. Manufacturing costs (excluding cost of pyrite) ranged from $5.51 to $25.40 per ton of 98 percent sulfuric acid. Plant investment cost ranged from $3.7 million to $35.5 million.

For purposes of the study effort, 1500 tons per day acid production capacity and a feed of 85 percent pyrite, 10 percent coal, and 5 percent gangue were chosen. Estimated processing cost (excluding raw

material costs and any by-product credit, i.e. low-pressure steam) for this type of plant is $7.63 per ton of 98 percent produced, with an estimated plant investment of $14.54 million.

Because of its comparatively high weight and low price, sulfuric acid is ordinarily marketed within a radius of 150 to 200 miles. Within the eight-state area covered by the investigation, the major outlet for sulfuric acid today and in the foreseeable future is and will be the phosphate fertilizer industry, which presently consumes approximately 40 percent of all sulfuric acid in the United States. Of the other uses of sulfuric acid, ammonium sulfate (also used extensively in fertilizer manufacture), titanium dioxide, petroleum refining, and steel making are the most significant.

To evaluate the need for a pyrite-based sulfuric acid plant, four major marketing areas which are reasonably close to the potential pyrite source areas were investigated. The investigated areas were: Pittsburgh, Pennsylvania; Cairo, Illinois; St. Louis, Missouri; and Chicago, Illinois. Pittsburgh is too far away to serve as an economic supply point to the Midwest fertilizer market. The other three areas offer reasonably attractive possibilities for a large, new sulfuric acid plant, so long as all or a major portion of production would be captive and related to fertilizer production. For an acid plant to be advantageously located with respect to potential pyrite supply and still be in a position to compete effectively in the fertilizer industry, the St. Louis and Cairo areas were judged preferable. Since Cairo is closer to possible pyrite

sources in Pennsylvania and southern Illinois (thereby minimizing potential freight costs) it was selected as the location to consider for an integrated pyrite-based fertilizer operation.

In order to evaluate the economic effect of a pyrite-based operation contrasted with a brimstone-based operation, a hypothetical situation was developed wherein phosphate fertilizer would be produced at Cairo, using pyrite feed obtained either from southern Illinois or the Pennsylvania region. To assess the competitive situation, an alternative was calculated, involving a similar phosphate fertilizer plant using brimstone (elemental sulfur), and located in Cairo or Baton Rouge, Louisiana. The price of brimstone was assumed to be $38 per long ton, f.o.b. Gulf Coast port (December 1967 quoted price). Under the conditions assumed, the net price payable to a coal company for an 85 percent pyrite feed may range from a negative value of $1.50 per ton to approximately $3.73 per ton, f.o.b. the fertilizer plant. If an additional penalty is imposed on the pyrite operation to reflect the risk associated with the higher capital cost required, the price payable for pyrite becomes lower.

2.5.3 The Chemico Study

The Chemico "High Sulfur Combustor Study" examined preliminary designs and evaluations of several combustion and flue gas treating systems for processing high sulfur fuels that may be drawn off from the rejects of coal washing. These fuels (i.e., washing rejects) will need to be tailored to specifications that depend first on the require-

ments of available processes for sulfur value recovery and second on the limitations of combustion equipment with respect to ash. The High Sulfur Combustion (HSC) fuel specifications can evidently be satisfied by appropriately re-combining selected portions of reject material from deep cleaning of coal.

Four sample HSC fuel compositions are tabulated in Table II together with product and cost data on six processing systems for these fuels. The operating context in each case is one of a number of typical site possibilities in the bituminous coal-producing area comprised of Pennsylvania, Ohio, West Virginia, Indiana, and Illinois.

Forward estimates of selling prices of the four products are:

Steam per M pounds	$ 0.65
Electricity per KWH	0.0075
Sulfur per long ton	25.00
Sulfuric acid per net ton	12.75

If these prices prevail, the estimates of economic benefit, if any, treated as credits to coal cleaning costs, are as shown below:

	CASE A M$	CASE B M$	CASE C M$	CASE D M$	CASE D3 M$	CASE E M$
Gain after Tax	1,760	(420)	(1,960)	690	4,700	4,230
Clean Coal M Ton/Year	7,100	2,300	920	7,100	7,100	3,500
Netback per Ton of Clean Coal	$0.25	($0.18)	($2.13)	$0.10	0.66	$1.21

TABLE II
HSC FUEL COMPOSITIONS, PRODUCTS, INVESTMENT, AND OPERATING COSTS

	CASE A	CASE B	CASE C PROTOTYPE	CASE D	CASE D3	CASE E
High Sulfur Fuel Composition						
% Total Sulfur	33.1	18.3	11.7	11.7	11.7	7.9
% Total Ash	61.0	42.5	33.8	33.8	33.8	28.8
Sulfur to Coal Weight Ratio	1.8	0.4	0.2	0.2	0.2	0.12
Percent SO_2 in Flue Gas	6.0	2.0	1.2	1.2	1.2	0.7
Products for Sale						
Energy as Steam - M Lbs/Hr	500	500	500	3,500	3,500	3,500
Energy as Electric Capacity - Megawatts			50	500	500	500
Sulfur Value as Sulfuric Acid - M Net Tons per Year	610	208			753	473
Sulfur Value as Sulfur - M Long Tons per year			31	233		
Co-Produced Clean Coal						
M Tons per year	7,100	2,300	920	7,100	7,100	3,500
TOTAL INVESTMENT IN HSC SYSTEMS	M$18,340	M$18,600	M$29,270	M$128,520	M$126,520	M$125,700
ANNUAL COST OF OPERATION BEFORE U.S. INCOME TAX	6,990	6,060	7,530	34,500	29,000	27,900
COST OF ENERGY EXTRACTION						
Steam per M Lbs	$ 3.00	$ 1.60				
Electricity per MWH			$ 14.50	$ 7.00	$ 7.00	$ 5.80
COST OF SULFUR VALUE EXTRACTION						
Sulfuric Acid per Net Ton	($ 8.20)	($ 2.00)			$ 3.50	$ 10.00
Sulfur per Long Ton			$ 57.00	$ 28.00		

NOTE: "Cost" does not include any charge for the HSC Fuels. Unit costs of products reflect an adjustment for "pollution control".

In CASE A and CASE B the cost of sulfuric acid manufacture is less than the cost of pollution control, hence the figures in () parenthesis.

SOURCE: Reference 25.

Case C is intended for possible construction as a prototype or demonstration plant. The four other case studies, taken together, amount to a preliminary exploration of the range of possible operating conditions. Any specific coal cleaning situation will need to be examined in detail for applicability to the high sulfur combustor concept. Washability of the coal and proximity to sulfuric acid consumers were found to be major determinants of the choice of technology and economic expectations. The manufacture of sulfur for conversion to sulfuric acid after shipment compares unfavorably with manufacture and direct shipment of sulfuric acid unless very large tonnages are to be shipped long distances by rail.

3.0 CONCLUSIONS

1. Information was developed on the sulfur forms and distribution of sulfur in coal samples from mines which were producers of utility coal. Related washability studies were performed to assess the effects of specific gravity and size reduction on the liberation and separation of pyritic sulfur and ash from coals. Data on 322 samples were reported by the Bureau of Mines and data on 67 samples were reported by the Illinois Geological Survey. This effort is continuing.

2. An evaluation of the data from 322 mines sampled showed that approximately 30 percent of these mines have coal that washed to a total sulfur content of 1 percent or less. Both the distribution and release potential of the sulfur in coals varies between the regions and coals within the region.

3. The Illinois Geological Survey data indicated that there are only a few Illinois coals whose sulfur content can be reduced to 1.5 percent or less. Coals capable of this amount of sulfur reduction had only 2 percent or less sulfur in the raw coal samples.

4. An evaluation of data obtained from 195 coal samples from the Appalachian region coal bed showed that significant total sulfur reductions are obtainable at yields of 70 to 80 percent.

5. An evaluation of data obtained from 13 coal samples from the Southern Appalachian region showed percentage reductions in pyritic sulfur contents (via washing) similar to those for Northern Appalachian coals. However, due to the low pyritic sulfur content of the southern coals, the attractiveness for cleaning is not as great.

6. The Illinois Geological Survey concluded that, for the (Illinois) coals tested for washability, two-inch-diameter core sample data correlated very closely with face sample data.

7. All existing commercial coal cleaning processes with the exception of froth flotation proved effective in separating liberated pyrite from coal. Of the several innovative processes for pyrite liberation investigated, the two-stage flotation technique appears to show the greatest potential for scale-up to commercial operation. The degree of sulfur reduction was dependent on equipment, operating characteristics, and, of course, the characteristics of the coal being tested. The studies defined how sulfur reduction could be optimized.

8. Based on float-sink test results, an estimate was made of the physical desulfurization potential of eastern bituminous steam coal.[9] The estimate was based on washing at 3/8 inch top size with a 90 percent Btu recovery. The resulting estimates of cumulative availability by sulfur content for both clean and raw coal are given in Figure 12.

9. The technology exists for utilizing reject and middling products to recover sulfur values and generate energy. The variables are such (e.g., market for sulfur values, cost of coal, cleaning cost, transportation economics, plant cost) that economic generalizations are not possible and each case must be individually examined.

10. Physical cleaning, in general, will provide a higher Btu, lower ash, more uniform product. Monetary benefits will result from using physically cleaned coal. These benefits are attributable to

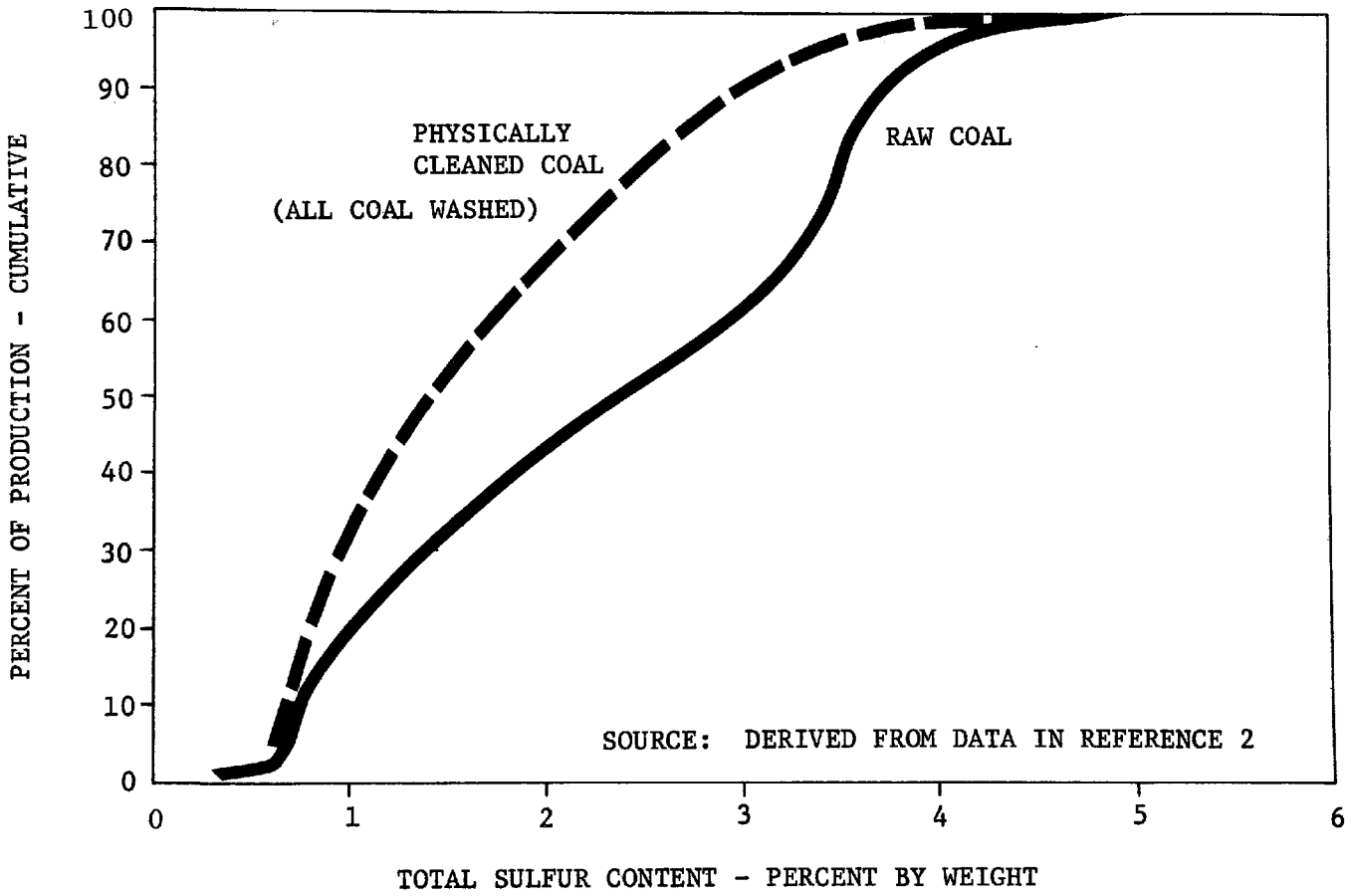


FIGURE 12
ESTIMATED PHYSICAL DESULFURIZATION POTENTIAL OF EASTERN BITUMINOUS STEAM COAL PRODUCTION

higher Btu content (of cleaned coal), an effective transportation cost saving, an ash disposal cost saving, a grinding cost saving, and a plant maintenance cost saving.[9]

11. Physical cleaning the higher sulfur content coals, thereby providing a higher BTU and lower ash product at high yield and reasonable cost, could provide fuel for a combustor employing a moderate-cost/moderate-capability supplemental stack gas cleaning system. This use of physical cleaning and flue gas cleaning could reduce the overall SO_2 emission control cost.

12. Physical cleaning of coal is essentially a proven technique with only degree (levels and amounts) to be quantified. The process is capable of providing a near-term, even though limited, benefit.

13. Physical cleaning of coal as a means to control sulfur oxides emissions will have the least impact on the economy. Wide-spread commerical application of physical cleaning will help maintain a viable coal industry and will permit increased use of coal, by far our most abundant fossil fuel resource.

14. Studies performed by the Bechtel Corporation and A. D. Little, Incorporated indicate that adequate technology exists, in the form of several commercially-used and proven processes, for recovery of sulfur values of pyrite materials as elemental sulfur or sulfuric acid and energy values as steam or electric power. These processes have been applied to mined pyrites but have not yet been applied to utilizing pyrite-bearing refuse from coal preparation plants as feedstock.

15. The Bechtel Corporation study indicates that several examined processes are technically capable of accepting coal cleaning refuse as feedstock, although certain of these processes require concentration of the refuse to increase its pyrite content.

16. All the processes considered by A. D. Little, Incorporated and the Bechtel Corporation for utilizing coal cleaning refuse require some degree of modification to accommodate the relatively low-pyrite, high-ash feedstock. Modification can be minimized by enriching the input air with pure oxygen.

17. There is a large and a relatively stable market for sulfuric acid. The attractiveness of processes for converting the sulfur content of coal preparation plant refuse to sulfuric acid is highly dependent on the market value of elemented sulfur.

18. Under conditions prevailing at the time of the A. D. Little, Inc. and the Bechtel Corp. studies, the refuse-combustion/sulfur-oxides-removal process and the fluid-bed roasting process were found to be economically viable.

19. The Chemico study indicated (i.e., at the time of the study) that by the use of high-sulfur refuse fuel of tailored composition to meet the requirements of especially designed combustors and commercially available boilers, generators and sulfur recovery processes, it appears possible to extract the energy and sulfur values of high-sulfur fuels on a commercial basis.

20. In view of the shipping costs resulting from the heavy weight of sulfuric acid, it may be highly advantageous for a sulfur recovery plant to be capable of producing sulfur as several different compounds (or in elemental form) especially in cases where the sulfur must be shipped to different points of consumption.

4.0 WASHABILITY STUDIES

This section outlines the procedures employed, details the number of samples obtained from various locations, summarizes the results of the washability studies, and reports on the findings of an effort that examined the comparability of coal core samples and face samples. The comparability of core samples and face samples effort was to determine whether useful washability data could be obtained from 2-inch diameter core samples. A more detailed description of sampling and washability procedures and an in-depth discussion of results can be found in References 3, 4, 5, 6, 7, and 8.

The principal purpose of the effort was to determine the sulfur forms and distribution of sulfur in coal samples from mines which were principally utility coal producers. Coal samples were obtained from the following coal regions:

1. Northern Appalachian region: the states of Maryland, Pennsylvania (bituminous), and Ohio and counties located in central and northern West Virginia.
2. Southern Appalachian region: the states of Tennessee, Virginia, and eastern Kentucky and some of the southern West Virginia counties.
3. Alabama region: the state of Alabama.
4. Midwest region: the states of Illinois, Indiana, and western Kentucky.
5. Western region: all states west of the Mississippi.

Generally, the washability data on the coals indicated that the total sulfur could be reduced by using some combination of stage crushing and specific gravity separation. The washability data were analyzed with the use of a specifically designed computer program.

4.1 Experimental Procedure - Collection of Coal Mine Samples

Coal samples were collected either from a fresh face in the mine or from the tipple (raw R.O.M.). The face samples were obtained by cutting channels approximately ten inches deep and wide enough to provide a sample of approximately 600 pounds.[8] Each channel was selected so as to be as representative as possible of coal being mined. Tipple samples were collected by taking increments at fixed time and/or weight intervals so as to insure that all working faces were represented in the gross sample.

4.2 Procedure for the Conduct of the Washability Studies

The sample preparation procedures by investigator with specific gravity test points for the washability studies are provided in Figure 13 and Table III. Each gross sample was air-dried and crushed to 1 1/2 inch top size using a single roll tooth crusher. The coal was then divided into required portions by means of cone and quartering. The preparation of each coal portion for float and sink tests was as indicated in Figure 13. The 100 mesh x 0 material, separated by screening from the coal fraction used for float and sink tests, was analyzed for ash, pyritic sulfur, and total sulfur.

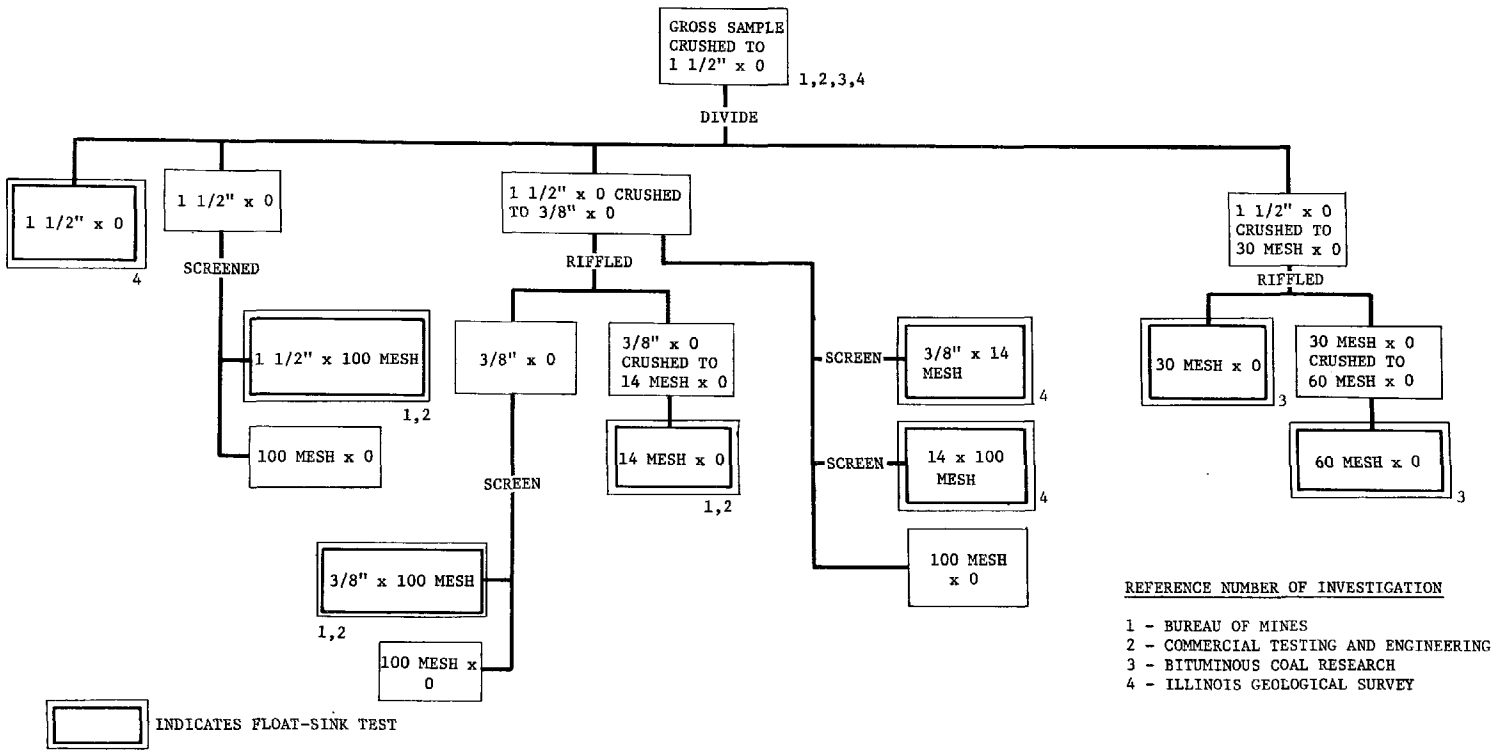


FIGURE 13
FLOW DIAGRAM SHOWING PREPARATION OF GROSS SAMPLE

TABLE III

TABLE OF FLOAT SINK TEST SIZES WITH SPECIFIC GRAVITIES

Investigator	Sizes Washed	Test Points (Specific Gravities)					
		1.25-1.29	1.30	1.30-1.39	1.40	1.60	1.90
Bureau of Mines	1 1/2 in. x 100 mesh		x		x	x	
	3/8 in. x 100 mesh		x		x	x	
	14 mesh x 0		x		x	x	
Commercial Testing and Engineering Company	1 1/2 in. x 100 mesh		x		x	x	x
	3/8 in. x 100 mesh		x		x	x	x
	14 mesh x 0		x		x	x	x
Bituminous Coal Research, Inc.	30 mesh x 0					x	
	60 mesh x 0 (p.c.)					x	
Illinois State Geological Survey	1 1/2 in. x 0	x		x	x	x	
	3/8 in. x 14 mesh	x		x	x	x	
	14 mesh x 100 mesh	x		x	x	x	

The float and sink analyses were conducted on the various fractions at specific gravities as indicated by Table III. After completing the float-and-sink analysis, the specific gravity fractions of the samples were analyzed for ash, pyritic sulfur, and total sulfur content.

Additional details of the float-sink tests are provided in Reference 8.

4.3 Results of Washability Data - Washability Computer Program

A computer program was used to interpolate the washability data to find the theoretical specific gravity of separation, yield, ash content, and pyritic and total sulfur contents for specific levels of yield or total sulfur. The values of the sulfur and yield interpolants were read into the computer and stored. In addition, the following data were entered for each mine sample: "state, county, town, mine, and bed codes; laboratory number, and laboratory identification code, bed-bench and size fraction codes; year of sample collection; company name, mine name, and county name; the specific gravity fractions of separation and their associated levels with the variables, ash, pyritic and total sulfur."[8] Using these data, three tables are printed out for each mine. These tables are: (1) the original cumulative washability data; (2) values of specific gravity of separation, yield, ash, and pyritic sulfur for requested levels of total sulfur; and (3) values of specific gravity of separation, yield, ash, pyritic sulfur, and total sulfur for the requested levels of yield.

A second computer program was written to make a statistical evaluation of the washability data. This program calculated averages and the standard deviation (sigma) values.

The computer program was used to calculate the percentages of total recovery of ash, pyritic sulfur, and total sulfur for the desired levels of interpolation. Next, the program was used to calculate the averages and standard deviations of the ash, pyritic sulfur, and total sulfur. These averages and standard deviation values were found for each bed and the required data accumulated for similar averages for the region. Also, the averages and standard deviation values were calculated for each set of interpolated values at the various yield levels.

4.4 Program Results

The average composition of the coals evaluated in the Bureau of Mines study*was 14.4 percent ash, 2.05 percent pyritic sulfur and 3.23 percent total sulfur.[8] The results generally indicated that the largest reduction in ash and sulfur through washing was obtained by reducing coal top size from 1 1/2 inches to 3/8 inch. Crushing from 3/8 inch to 14 mesh showed relatively lower ash and sulfur reduction.

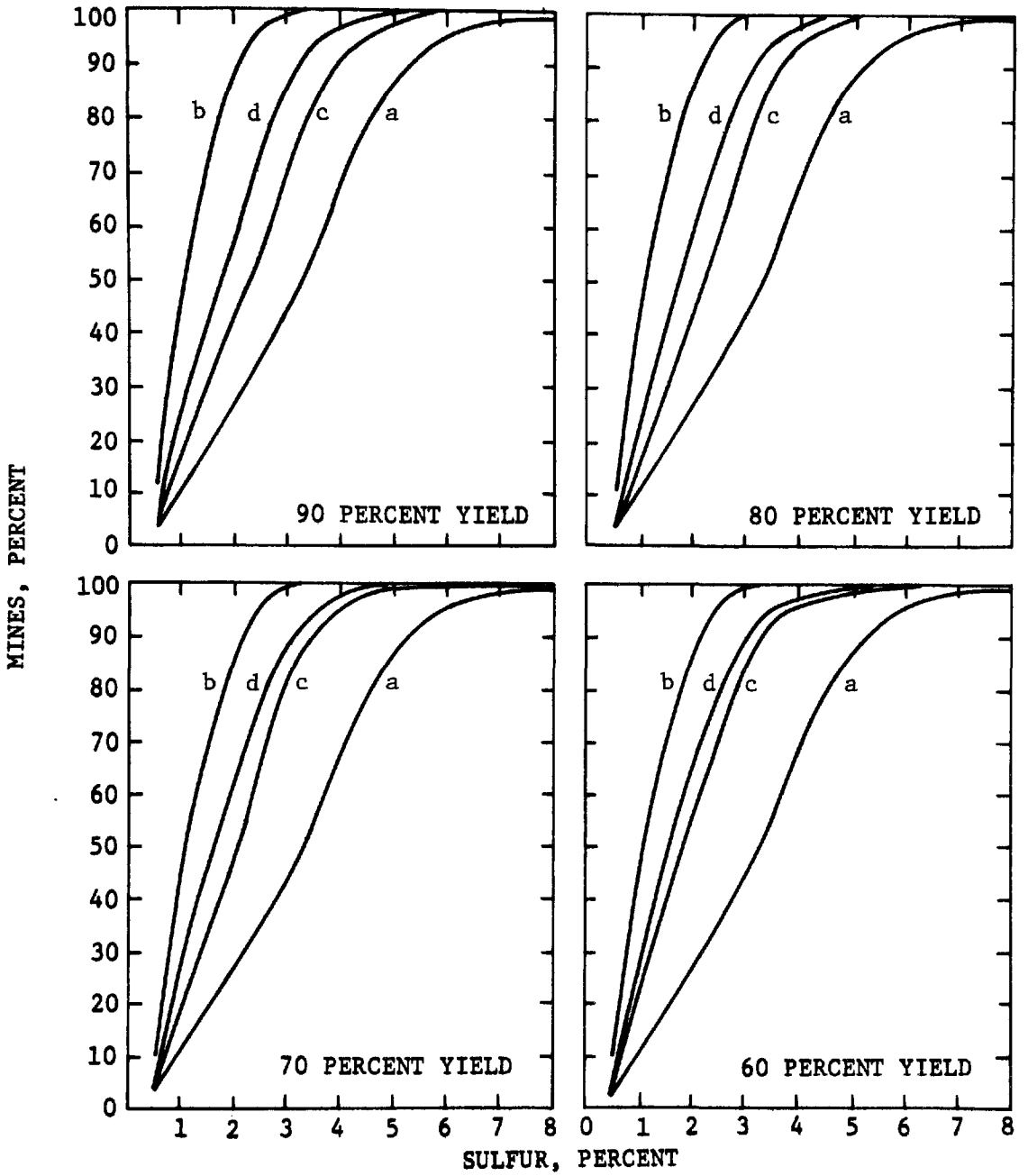
*Data from the Commercial Testing and Engineering Company investigations are reported by the Bureau of Mines.

Summary data covering the 322 coal samples evaluated by the Bureau of Mines are as follows:[8]

Percent Yield	No. of Samples	Ash, Percent (Raw Avg.: 14.4, Sigma: 5.8) Average	Ash, Percent Sigma*	Pyritic Sulfur, Percent (Raw Avg.: 2.05, Sigma: 1.35) Average	Pyritic Sulfur Sigma	Total Sulfur, Percent (Raw Avg.: 3.23, Sigma: 1.75) Average	Total Sulfur Sigma
				1 1/2 Inch Top Size			
60	260	5.8	2.3	0.72	0.57	1.95	1.06
70	290	6.4	2.7	0.79	0.59	2.03	1.07
80	284	7.1	2.8	0.89	0.65	2.13	1.12
90	168	7.2	2.4	1.00	0.68	2.27	1.21
				3/8 Inch Top Size			
60	25.	5.1	2.2	0.57	0.48	1.82	1.04
70	287	5.6	2.4	0.61	0.48	1.83	1.00
80	277	6.3	2.4	0.68	0.49	1.92	1.04
90	145	6.5	2.2	0.75	0.56	1.95	1.12
				14 Mesh Top Size			
60	270	4.6	2.1	0.46	0.40	1.70	0.98
70	298	5.2	2.3	0.50	0.39	1.72	0.96
80	274	5.9	2.2	0.57	0.42	1.79	0.99
90	136	6.0	2.0	0.59	0.48	1.79	1.07

The sulfur reductions of these coals attained by washing are further summarized in Figure 14. This figure indicates that significant total sulfur reductions are attainable by removing heavy impurities. At 60 percent yield, 20 to 25 percent of the mine samples showed a 1 percent or less total sulfur product.

*Sigma (σ) is the standard deviation value.



(a) RAW COAL TOTAL SULFUR CONTENT CURVE;
(b) RAW COAL ORGANIC SULFUR CONTENT CURVE;
(c) WASHED COAL TOTAL SULFUR CONTENT COAL CURVE WHEN RAW COAL WAS CRUSHED TO MINUS 1½ INCHES; AND,
(d) WHEN RAW COAL WAS CRUSHED TO MINUS 14 MESH.

SOURCE: REFERENCE 8

FIGURE 14
WASHABILITY SUMMARY OF ALL COALS

An evaluation of the data from the 322 mines sampled showed that approximately 30 percent of these mines have coal that washed to a total sulfur content of 1 percent or less. On crushing to 1 1/2 inch top size, significant reductions in sulfur content were attainable by removing 10 or 20 percent of the heaviest material. Furthermore, the total sulfur content was reduced by approximately 50 percent in more than half of the samples collected by crushing of the coal prior to removing the heaviest impurities. Both the distribution and release potential of the sulfur in coals varies between the regions and the coals within the region.

The Illinois Geological Survey washability studies indicated that most Illinois coals have a total sulfur content of 3 to 5 percent and there are only a few Illinois coals whose sulfur content can be reduced to 1.5 percent or less. The coals capable of this amount of sulfur reduction had only 2 percent or less sulfur in the raw coal samples.

With regard to the forms of sulfur in the coals, it was found that approximately 50 percent of the sulfur in the average Illinois coal was in the pyritic form. The average pyritic sulfur reduction was approximately 60 percent with an 80 percent yield and 75 percent with a 40 percent yield.

Usually, the float coal fractions had less sulfur when the coal was crushed to finer sizes. In many of the coals tested, however, the differences were not great enough to warrant grinding the coals to finer sizes for sulfur reduction.

4.4.1 Northern Appalachian Region

One hundred and ninety-five coal bed samples were collected from the following four states of the Appalachian region:

1. Maryland - 32 samples
2. Ohio - 48 samples
3. Pennsylvania - 90 samples
4. Northern West Virginia - 25 samples.

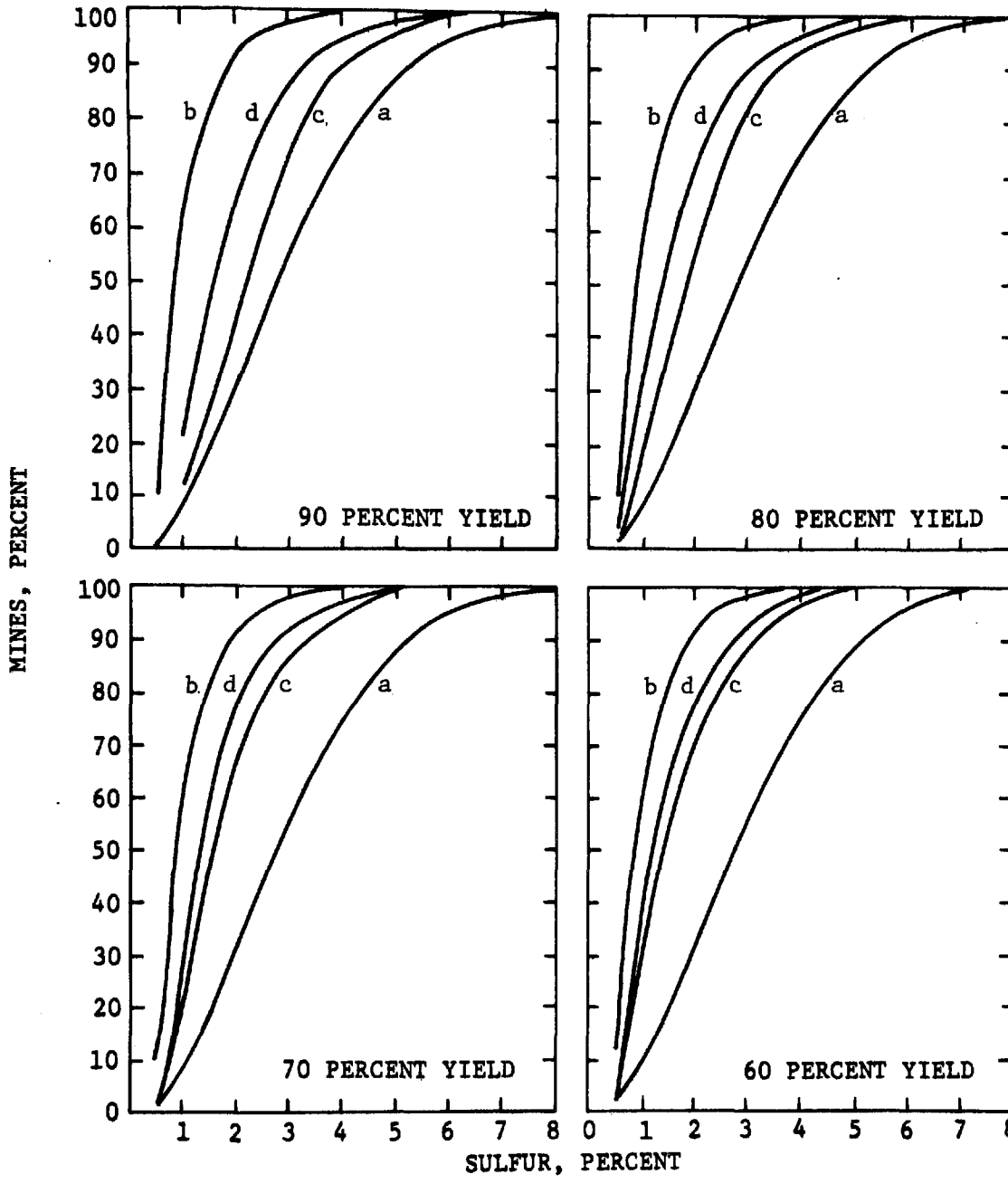
The average composition of the raw coal of the region was 14.7 percent ash, 2.03 percent pyritic sulfur, and 3.07 percent total sulfur. An analysis of the data indicated that crushing the raw coal to 1 1/2 inch top size resulted in an average pyritic sulfur reduction of 0.95 percentage points at 90 percent yield and 1.12 percentage points at 80 percent yield. Crushing the coal to 3/8 inch top size resulted in an average pyritic sulfur reduction compared to raw coal of 1.25 percentage points at 90 percent yield and 1.4 percentage points at 80 percent yield. Crushing the coal to 14 mesh top size resulted in an average pyritic sulfur reduction compared to raw coal of 1.46 percentage points at 90 percent yield and 1.52 percentage points at 80 percent yield.

Summary data covering the 195 Northern Appalachian region coal samples evaluated by the Bureau of Mines are as follows:[8]

Percent Yield	No. of Samples	Ash, Percent (Raw Avg.: 14.7, Sigma: 6.0) Average	Ash, Sigma	Pyritic Sulfur, Percent (Raw Avg.: 2.03, Sigma: 1.24) Average	Pyritic Sulfur, Sigma	Total Sulfur, Percent (Raw Avg.: 3.07, Sigma: 1.59) Average	Total Sulfur, Sigma
				1 1/2 Inch Top Size			
60	169	5.8	2.6	0.68	0.54	1.73	0.96
70	180	6.6	2.9	0.79	0.59	1.83	1.00
80	169	7.4	3.0	0.91	0.70	1.96	1.11
90	99	7.4	2.4	1.08	0.67	2.25	1.15
				3/8 Inch Top Size			
60	159	5.2	2.4	0.50	0.45	1.57	0.93
70	179	5.8	2.7	0.57	0.49	1.62	0.94
80	163	6.5	2.6	0.63	0.49	1.68	0.98
90	86	6.7	2.2	0.78	0.57	1.90	1.11
				14 Mesh Top Size			
60	163	4.7	2.2	0.39	0.35	1.45	0.86
70	181	5.4	2.6	0.44	0.39	1.49	0.87
80	161	6.0	2.3	0.51	0.40	1.55	0.91
90	81	6.2	2.0	0.57	0.45	1.69	1.01

Figure 15 shows the percentage of mines versus sulfur content relationship derived from analyses of coals collected from the Northern Appalachian region. This figure indicates that 32 percent of the mines sampled contained coal with less than 2 percent total sulfur. Upon crushing to 1 1/2 inch top size with 90 percent yield, 43 percent of the mines sampled contained less than 2 percent total sulfur. At 80 percent yield the value increased to 68 percent with less than 2 percent sulfur. In general, significant total sulfur reductions are obtainable at yields of 70 to 80 percent.

The results of sampling various coal beds of the Northern Appalachian region are discussed in the following sections.



(a) RAW COAL TOTAL SULFUR CONTENT CURVE;
(b) RAW COAL ORGANIC SULFUR CONTENT CURVE;
(c) WASHED COAL TOTAL SULFUR CONTENT COAL CURVE WHEN RAW COAL WAS CRUSHED TO MINUS 1½ INCHES; AND,
(d) WHEN RAW COAL WAS CRUSHED TO MINUS 14 MESH.

SOURCE: REFERENCE 8

FIGURE 15
WASHABILITY OF NORTHERN APPALACHIAN REGION COALS

4.4.1.1 Sewickley Coal Bed. Thirteen Sewickley coal bed samples were collected from the following four Northern Appalachian states:

1. Maryland - 2 samples
2. Ohio - 9 samples
3. Pennsylvania - 1 sample
4. West Virginia - 1 sample

The total sulfur content of this coal is high, averaging over 2.5 percent (with $\sigma \approx 1.37$) at 60 percent yield. In general, this coal was quite refractory, providing small to only moderate reductions of ash and total sulfur contents as a result of crushing. However, the pyritic sulfur reduction was high due to the coarseness of the pyrite which reported to the high specific gravity material.

The organic sulfur content of coals from the Sewickley bed varied considerably and was generally over 1.5 percent. The high percentage reduction in pyritic sulfur was reflected in total sulfur reductions ranging from 23 percentage points at 90 percent yield to 33 percentage points at 60 percent yield when the coals were crushed to 3/8 inch top size. Further crushing did not significantly reduce total sulfur content.

4.4.1.2 Pittsburgh Coal Bed. Thirty-six samples from the Pittsburgh coal bed were collected from the following four Northern Appalachian Region states:

1. Maryland - 1 sample
2. Ohio - 16 samples
3. Pennsylvania - 5 samples
4. West Virginia - 14 samples

The average characteristics of the raw samples collected from the Pittsburgh coal bed are 12.4 percent ash (σ = 5.8), 2.16 percent pyritic sulfur (σ = 0.92), and 3.61 percent total sulfur (σ = 1.21). Crushing these coals to 1 1/2 inch top size provided 90 percent average yield values of 6.7 percent ash (σ = 1.1), 1.29 percent pyritic sulfur (σ = 0.58), and 2.77 total sulfur (σ = 0.92). The 80 percent average yield values were 5.9 percent ash (σ = 1.5), 1.08 percent pyritic sulfur (σ = 0.58), and 2.62 percent total sulfur (σ = 0.91). Thus, significant reductions were effected with only 1 1/2 inch top size crushing.

Crushing these coals to 3/8 inch top size provided 90 percent average yield values of 6.4 percent ash (σ = 0.9), 1.05 percent pyritic sulfur (σ = 0.53), and 2.54 percent total sulfur (σ = 0.89). The 80 percent average yield values* are 5.5 percent ash (σ = 1.2), 0.9 percent pyritic sulfur (σ = 0.51), and 2.44 percent total sulfur (σ = 0.86). Improvements obtained by further crushing to 14 mesh were small, as was the case in crushing from 1 1/2 inch to 3/8 inch top size.

4.4.1.3 Upper Freeport Coal Bed. Thirty Upper Freeport coal bed samplers were collected from the following states:

1. Maryland - 6 samples
2. Pennsylvania - 18 samples
3. West Virginia - 6 samples.

*hereafter the term "yield values" will be used to denote "average yield values."

The average characteristics of raw samples collected from the Upper Freeport coal bed are 17.2 percent ash (σ = 5.3), 1.72 percent pyritic sulfur (σ = 0.99) and 2.42 percent total sulfur (σ = 1.10). Crushing these coals to 1 1/2 inch top size provided 90 percent yield values of 9.1 percent ash (σ = 2.9), 1.05 percent pyritic sulfur (σ = 0.72), and 1.81 percent total sulfur (σ = 0.89). The 80 percent yield values are 8.2 percent ash (σ = 2.3), 0.76 percent pyritic sulfur (σ = 0.46), and 1.45 percent total sulfur (σ = 0.57).

Crushing these coals to 3/8 inch top size provided 90 percent yield values of 7.7 percent ash (σ = 1.6), 0.54 percent pyritic sulfur (σ = 0.52), and 1.20 percent total sulfur (σ = 0.74). The 80 percent yield values are 7.4 percent ash (σ = 2.3), 0.48 percent pyritic sulfur (σ = 0.29), and 1.16 percent total sulfur (σ = 0.41).

Crushing to 14 mesh top size provided 90 percent yield values of 7.1 percent ash (σ = 1.7), 0.41 percent pyritic sulfur (σ = 0.34), and 1.06 percent total sulfur (σ = 0.55). The washability data indicate impurity release at high yields when the coal is crushed to 1 1/2 inch top size with additional significant release upon crushing to 3/8 inch top size.

The washability data indicate that this coal is an excellent example of a coal which can be significantly desulfurized by physical means.

4.4.1.4 Lower Freeport Coal Bed. Twelve samples were collected from the following states:

1. Maryland - 1 sample
2. Ohio - 2 samples
3. Pennsylvania - 9 samples.

The average characteristics of the raw samples collected from the Lower Freeport coal bed are 12.9 percent ash (σ = 3.5), 1.72 percent pyritic sulfur (σ = 0.75), and 2.45 percent total sulfur (σ = 0.78). Crushing these coals to 1 1/2 inch top size provided 90 percent yield values of 7.2 percent ash (σ = 2.0), 0.85 percent pyritic sulfur (σ = 0.24), and 1.61 percent total sulfur (σ = 0.36). The 80 percent yield values are 6.3 percent ash (σ = 2.0), 0.69 percent pyritic sulfur (σ = 0.27), and 1.42 percent total sulfur (σ = 0.36).

Crushing these coals to 3/8 inch top size provided 90 percent yield values of 6.5 percent ash (σ = 2.2), 0.52 percent pyritic sulfur (σ = 0.21), and 1.23 percent total sulfur (σ = 0.33). The 80 percent yield values are 5.3 percent ash (σ = 1.8), 0.35 percent pyritic sulfur (σ = 0.18), and 1.02 percent total sulfur (σ = 0.29). Further crushing to 14 mesh top size proved to be of very limited value.

The washability data indicate that coal from the lower Freeport coal bed is a good example of coal which can be significantly desulfurized by physical means. When this coal is crushed to 3/8 inch top size, over 70 percent of the pyritic sulfur can be removed at an 80 percent yield.

4.4.1.5 Upper Kittanning Coal Bed. Nine coal samples were collected from the following two states:

1. Maryland - 1 sample
2. Pennsylvania - 8 samples.

The average characteristics of the raw samples collected from the Upper Kittanning coal bed are 16.7 percent ash (σ = 7.4), 1.78 percent pyritic

sulfur (σ = 1.19), and 2.37 percent total sulfur (σ = 1.29). Crushing these coals to 1 1/2 inch top size provided 80 percent yield values of 7.1 percent ash (σ = 0.5), 0.48 percent pyritic sulfur (σ = 0.39), and 1.07 percent total sulfur (σ = 0.46). Crushing to 3/8 inch top size provided 80 percent yield values of 6.4 percent ash (σ = 0.5), 0.33 percent pyritic sulfur (σ = 0.33), and 0.89 percent total sulfur (σ = 0.37). Further crushing to 14 mesh top size proved to be of no practical value.

The sampled data indicated that Upper Kittanning coal is a good example of coal that can be significantly desulfurized. The average sulfur content of these coals decreased from the raw coal value of 2.37 percent to 0.89 percent upon crushing to 3/8 inch top size and processing to provide an 80 percent yield.

4.4.1.6 Middle Kittanning Coal Bed. Twenty-three coal samples were collected from the following three states:

1. Ohio - 11 samples
2. Pennsylvania - 10 samples
3. West Virginia - 2 samples.

The average characteristics of the raw coal samples collected from the Middle Kittanning coal bed are 12.7 percent ash (σ = 5.2), 2.25 percent pyritic sulfur (σ = 1.52), and 3.35 percent total sulfur (σ = 2.02). Crushing these coals to 1 1/2 inch top size provided 80 percent yield values of 6.5 percent ash (σ = 3.2), 0.95 percent pyritic sulfur (σ = 1.09), and 2.02 percent total sulfur (σ = 1.45). Crushing to 3/8 inch top size provided 80 percent yield values of 5 percent ash (σ = 2.1), 0.52 percent

pyritic sulfur (σ = 0.34), and 1.56 percent total sulfur (σ = 0.71). Further crushing to 14 mesh top size proved to be of very limited values.

4.4.1.7 Lower Kittanning Coal Bed. Thirty-seven coal samples were collected from the following three states:

1. Maryland - 3 samples
2. Ohio - 5 samples
3. Pennsylvania - 29 samples.

The average characteristics of the raw samples collected from the Lower Kittanning coal bed are 15.1 percent ash (σ = 6.8), 2.31 percent pyritic sulfur (σ = 1.46), and 3.25 total sulfur (σ = 1.73). Crushing these coals to 1 1/2 inch top size provided 80 percent yield values of 6.9 percent ash (σ = 2.7), 0.87 percent pyritic sulfur (σ = 0.71), and 1.77 percent total sulfur (σ = 0.94). Crushing to 3/8 inch top size provided 80 percent yield values of 6.1 percent ash (σ = 2.7), 0.60 percent pyritic sulfur (σ = 0.52), and 1.47 percent total sulfur (σ = 0.75). Crushing to 14 mesh top size provided 80 percent yield values of 5.5 percent ash (σ = 2.3), 0.52 percent pyritic sulfur (σ = 0.40), and 1.39 percent total sulfur (σ = 0.62). The corresponding reduction in sulfur amounts to approximately 55 percent on crushing to 3/8 inch top size and 57 percent on crushing to 14 mesh top size.

4.4.2 Southern Appalachian Region Coals

The 13 samples from the Southern Appalachian region coal bed were collected from the following three states:

1. Tennessee - 6 samples

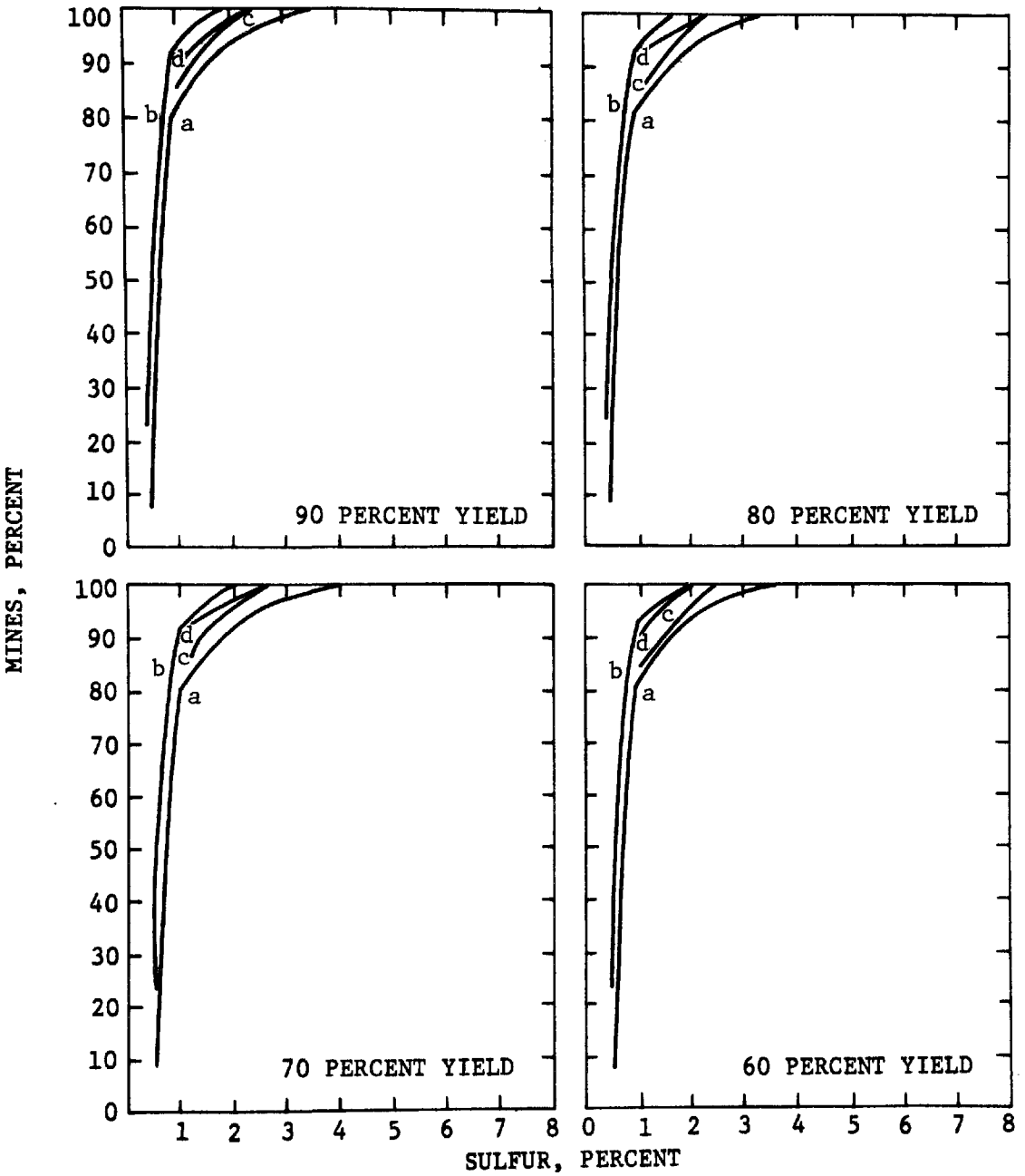
2. Southern West Virginia - 3 samples

3. Virginia - 4 samples.

The average raw coal of the region contained 11.2 percent ash, 0.29 percent pyritic sulfur, and 0.93 percent total sulfur. These are generally low-sulfur-content coals averaging less than 1 percent total sulfur content. Because the pyritic sulfur is so low, crushing of these coals to release sulfur would be of almost no benefit, although the pyritic sulfur reduction owing to crushing and reduced yield is very good. The sulfur reduction of these coals attained by washing is summarized below and in Figure 16.

Summary data covering the 13 Southern Appalachian region samples evaluated by the Bureau of Mines are as follows:[8]

Percent Yield	No. of Samples	Ash, Percent (Raw Avg.: 11.2, Sigma: 5.3)		Pyritic Sulfur, Percent (Raw Avg.: 0.29, Sigma: 0.52)		Total Sulfur, Percent (Raw Avg.: 0.93, Sigma: 0.80)	
		Average	Sigma	Average	Sigma	Average	Sigma
		1 1/2 Inch Top Size					
60	6	4.0	1.6	0.15	0.21	0.98	0.65
70	12	4.0	1.7	0.10	0.17	0.81	0.49
80	12	4.3	2.2	0.10	0.18	0.81	0.50
90	8	4.8	2.1	0.14	0.28	0.90	0.66
		3/8 Inch Top Size					
60	5	4.1	0.9	0.14	0.19	1.01	0.68
70	10	3.9	1.7	0.09	0.16	0.81	0.51
80	12	3.8	2.2	0.08	0.13	0.78	0.45
90	8	3.5	2.0	0.12	0.25	0.87	0.63
		14 Mesh Top Size					
60	9	2.8	1.3	0.07	0.09	0.84	0.44
70	13	3.2	1.6	0.07	0.10	0.77	0.39
80	12	3.9	1.9	0.08	0.14	0.78	0.44
90	8	4.5	1.9	0.11	0.22	0.84	0.58



(a) RAW COAL TOTAL SULFUR CONTENT CURVE; SOURCE: REFERENCE 8
(b) RAW COAL ORGANIC SULFUR CONTENT CURVE;
(c) WASHED COAL TOTAL SULFUR CONTENT COAL CURVE WHEN RAW COAL WAS CRUSHED TO MINUS 1½ INCHES; AND,
(d) WHEN RAW COAL WAS CRUSHED TO MINUS 14 MESH.

FIGURE 16
WASHABILITY OF SOUTHERN APPALACHIAN REGION COALS

4.4.3 Alabama Region Coals

Six samples were collected from the Alabama region. The average characteristics of the raw samples are 14 percent ash (σ = 3.7), 0.97 percent pyritic sulfur (σ = 0.99), and 1.66 percent total sulfur (σ = 1.11). Crushing the coals to 1 1/2 inch top size provided 80 percent yield values of 8.7 percent ash (σ = 2.3), 0.77 percent pyritic sulfur (σ = 0.76), and 1.54 percent total sulfur (σ = 0.89). Crushing to 3/8 inch top size provided 80 percent yield values of 8.2 percent ash (σ = 2.2), 0.71 percent pyritic sulfur (σ = 0.68), and 1.48 percent total sulfur (σ = 0.84). Crushing to 14 mesh top size provided 80 percent yield values of 6.9 percent ash (σ = 3.3), 0.47 percent pyritic sulfur (σ = 0.51), and 1.21 percent total sulfur (σ = 0.64). Processing to lower yields provided little additional sulfur reductions.

4.4.4 Midwest Region Coals

Eighty-two samples from the Midwest Region were reported by the Bureau of Mines from the following three states:

1. Illinois - 31 samples
2. Indiana - 17 samples
3. Kentucky (West) - 34 samples.

The average composition of the raw samples collected from the midwest region was 14.1 percent ash, 2.29 percent pyritic sulfur, and 3.92 percent total sulfur. Crushing these coals to 1 1/2 inch top size provided 90 percent yield values of 7.5 percent ash, 1.00 percent pyritic sulfur, and 2.76 percent total sulfur. The 70 percent yield values were

6.0 percent ash, 0.82 percent pyritic sulfur, and 2.61 percent total sulfur. Crushing to 3/8 inch top size did not provide significant improvements in ash and sulfur values.

Crushing these coals to 14 mesh top size provided 90 percent yield values of 6.7 percent ash, 0.77 percent pyritic sulfur, and 2.53 percent total sulfur. The 70 percent yield values were 5.1 percent ash, 0.66 percent pyritic sulfur, and 2.38 percent total sulfur. At 60 percent yield the values were 4.4 percent ash, 0.58 percent pyritic sulfur and 2.29 percent total sulfur.

Summary data covering the 82 Midwest region coal samples evaluated by the Bureau of Mines are as follows:

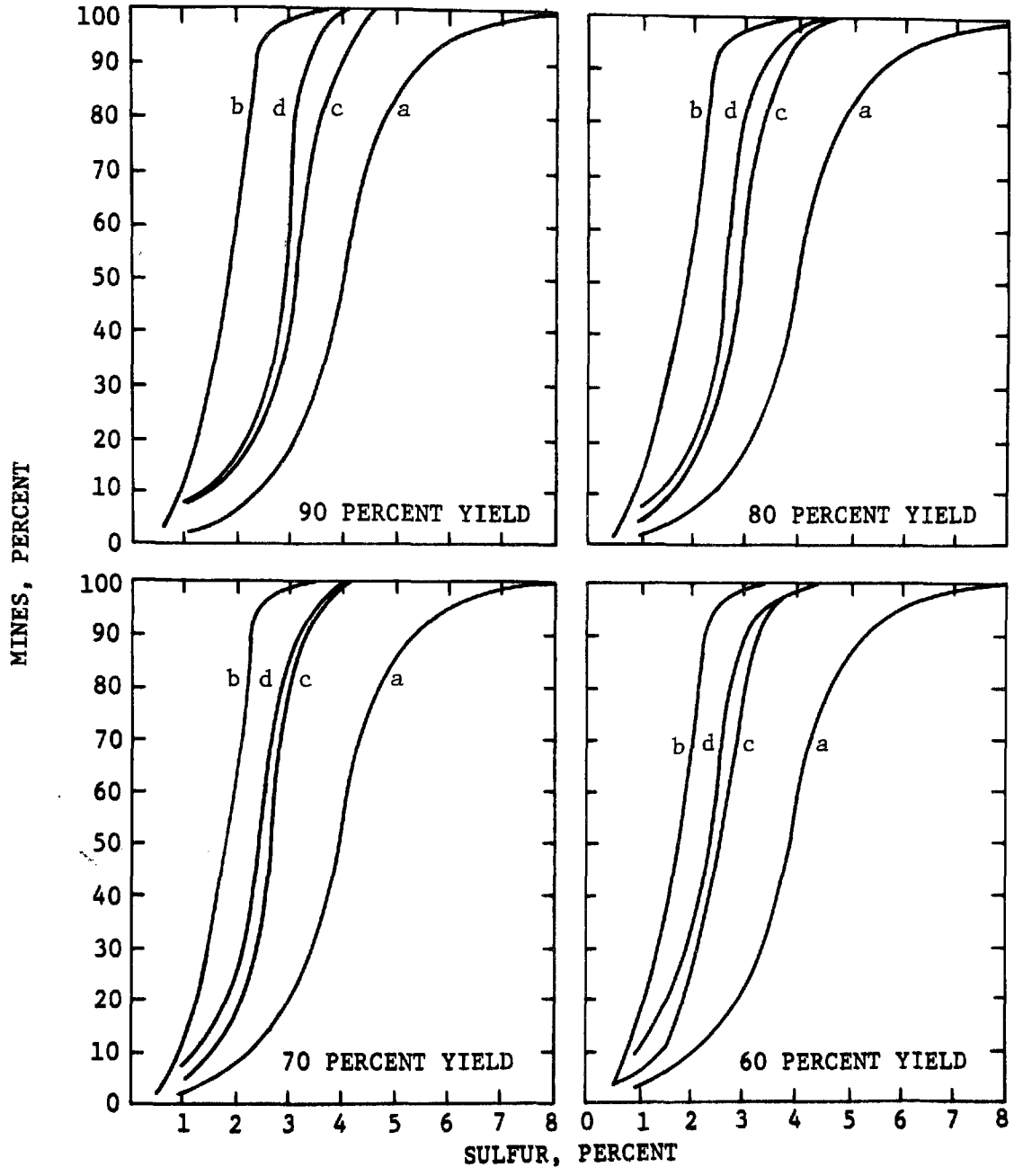
Percent Yield	No. of Samples	Ash, Percent (Raw Avg.: 14.1, Sigma: 4.8)		Pyritic Sulfur, Percent (Raw Avg.: 2.29, Sigma: 1.00)		Total Sulfur, Percent (Raw Avg.: 3.92, Sigma: 1.26)	
		Average	Sigma	Average	Sigma	Average	Sigma
				1 1/2 Inch Top Size			
60	61	5.4	1.2	0.75	0.32	2.49	0.70
70	73	6.0	1.6	0.82	0.35	2.61	0.69
80	79	7.0	1.9	0.97	0.45	2.72	0.78
90	42	7.5	1.6	1.00	0.48	2.76	0.97
				3/8 Inch Top Size			
60	62	4.7	1.1	0.66	0.25	2.42	0.70
70	73	5.3	1.4	0.73	0.30	2.47	0.74
80	79	6.4	1.7	0.86	0.37	2.60	0.78
90	35	6.9	1.6	0.85	0.34	2.59	0.86
				14 Mesh Top Size			
60	71	4.4	1.2	0.58	0.22	2.29	0.73
70	78	5.1	1.5	0.66	0.26	2.38	0.73
80	76	6.2	1.8	0.77	0.33	2.48	0.75
90	33	6.7	1.5	0.77	0.34	2.53	0.83

Figure 17 shows that 60 percent of the collected samples contained less than 2 percent organic sulfur. For top size crushing of 1 1/2 inch and less, over half of the pyritic sulfur is removed with 90 percent yield. The reasonable range of total sulfur in the final product as indicated in Figure 17 is 2-3 percent.

The results of sampling the various coal beds of the Midwest region are as follows:

4.4.4.1 Kentucky No. 9 Coal Bed. Thirteen samples from the Kentucky No. 9 coal bed were collected from Western Kentucky. The average composition of the raw samples was 11.4 percent ash (σ = 2.2), 2.22 percent pyritic sulfur (σ = 0.42), and 4.15 percent total sulfur (σ = 0.28). The pyritic sulfur reduction was significant at 90 percent yield and less. However, because of the high organic sulfur content of these coals they could not be physically cleaned to a total sulfur content of less than 2 percent.

4.4.4.2 Illinois Coal Beds. Twenty-one Illinois No. 6 coal samples were collected from the State of Illinois. The average composition of the raw samples was 15.2 percent ash (σ = 4.3), 2.11 percent pyritic sulfur (σ = 1.21), and 3.77 percent total sulfur (σ = 1.68). Crushing was of limited value in releasing impurities from these samples. Removal of the heaviest impurities provided significant reductions in the ash and pyritic sulfur contents of these samples. It was difficult to obtain a low total sulfur content with this coal because of the high percentages of organic sulfur present.



(a) RAW COAL TOTAL SULFUR CONTENT CURVE; SOURCE: REFERENCE 8
(b) RAW COAL ORGANIC SULFUR CONTENT CURVE;
(c) WASHED COAL TOTAL SULFUR CONTENT COAL CURVE WHEN RAW COAL WAS CRUSHED TO MINUS 1½ INCHES; AND,
(d) WHEN RAW COAL WAS CRUSHED TO MINUS 14 MESH.

FIGURE 17
WASHABILITY OF MIDWEST REGION COALS

4.4.5 Illinois Geological Survey Studies[7,11]

In addition to the Bureau of Mines reported studies, washability studies in two phases were conducted by the Illinois Geological Survey on samples taken from Illinois coal mines. During the first phase, 40 samples were taken from 35 Illinois coal mines located in most mining areas in the state, the number of samples being greater than the number of mines because several mines produced coal from more than one seam and the different seams were sampled separately.

During the second phase of the Illinois Geological Survey investigation, washability tests were made on 27 coal samples taken from most of the Illinois mines not sampled during the first phase. The coal samples (phases I and II) were obtained from the No. 1, No. 2, No. 4, No. 5, No. 6, No. 7, DeKoven, and Davis seams.

Float-sink tests indicated that only in those Illinois coals having relatively low-sulfur content, as mined, could the total sulfur content be reduced to 1.5 percent or less by washing techniques. Most Illinois coals, as mined, contain 3-5 percent sulfur. Float-sink tests indicate this level could be reduced to about 2.5 to 4 percent total sulfur.

In Phase I, only two of the 40 tested samples could be reduced to a total sulfur content of less than 1 percent at an 80 percent recovery. Five samples could be cleaned to less than 1.5 percent total sulfur with an 80 percent recovery. These five samples were all naturally-occurring low-sulfur coals. Of the 40 coals tested during Phase I, 10

samples could be cleaned to 2.5 percent sulfur or less than an 80 percent recovery. The above was obtained with top size crushing of 1 1/2 inches. Crushing to finer sizes did not provide additional significant sulfur reductions.

Due to the similarity of Phase I results between 1 1/2 inch and 3/8 inch top size testing and since 3/8 inch top size testing would allow the use of a smaller quantity of coal for washing and chemical tests, the following Phase II results are based on testing at 3/8 inch top size.

In Phase II, 4 out of the 27 samples tested had less than one percent total sulfur at recovery levels of 80, 60 or 40 percent. Of these four, one sample was obtained from a mine in current production and with appreciable unmined reserves. In addition to the above, one sample obtained from a large mine had float coal with less than 1.5 percent total sulfur content with an 80 percent recovery. None of the other samples could be washed, irrespective of yield, to less than 1.5 percent total sulfur.

4.4.6 Western Coal[8]

The examination of Western coals was initiated at a later date than for coals of the other regions. This is due to the preponderance of steam coal traditionally supplied by states east of the Mississippi. As interest in the vast reserves and the potential availability of Western coal developed, washability examinations were performed, concentrating on the higher sulfur coals, i.e., those coals in which a sulfur reduction potential would be most desirable.[9]

For this effort, twenty-six coal samples from the Western region were collected from the following six states:

1. Iowa - 6 samples
2. Oklahoma - 4 samples
3. Kansas - 4 samples
4. Arkansas - 3 samples
5. Missouri - 4 samples
6. Colorado - 5 samples.

All of the Western coal samples, with the exception of those from Colorado, are from the Western Interior region. Colorado lies in the Rocky Mountain region.

The average composition of raw coal from the Western region was 14.5 percent ash, 2.48 percent pyritic sulfur, and 3.72 percent total sulfur. Coals from the Western Interior region are characteristically high in sulfur content, regardless of sulfur treatment employed. Coals from the Rocky Mountain region conversely are characteristically of low sulfur content, often less than one percent sulfur content, and range in rank from bituminous coal to lignite, with sub-bituminous predominating.

4.4.7 Extension of Float-Sink Test to Finer Grinds[6,10]

Washability studies were extended in a separate effort (ref. Figure 13) to cover finer sizes of coal at a specific gravity of 1.60. The coal sizes studied were the 30 mesh x 0 size and the "as fired" or pulverized coal (p.c.) grind. All coal in the p.c. grind is minus 60 mesh with a minimum of 80 percent of the coal minus 200 mesh. The 30 mesh x 0 size represented the lower limit in sizing that would contain a size range of

pyrite typical of a utility pulverizer's recycle load. The coals "as fired" (or p.c. grind) were of interest because potentially the maximum pyrite liberation occurs, based on present utilization, with this degree of pulverization.

The results of the float-sink analysis of the coal samples are discussed in terms of a first series of 70 samples and an additional series of 20 samples. The first series of 70 coals came from three geographical areas: Western Pennsylvania, Eastern Ohio, and Illinois. Maximum pyritic sulfur reduction obtained at the 30 x 0 mesh size was 93.7 percent with an Ohio No. 6 coal; the minimum pyritic sulfur reduction obtained was 51.2 percent with an Illinois No. 6 coal. At the p.c. grind, 95 percent of the pyritic sulfur was removable from a Pennsylvania Lower Freeport coal while the minimum percentage of pyritic sulfur removal was 54.5 percent with a Pennsylvania Middle Kittanning coal which had a very low R.O.M. pyritic sulfur content. Total sulfur reductions covered a much wider range since the percentages of organic sulfur, which was not removable, quite significantly affected the percent reduction.

The second series of 20 coals came from three geographical areas: (1) the Southern Appalachian, (2) Western Interior, and (3) Rocky Mountain regions. The total sulfur in raw R.O.M. samples ranged from 0.32 to 6.37 percent by weight. Pyritic sulfur levels ranged from 0.09 to 4.66 percent by weight. The evaluation of the second series of 20 coals differed markedly from the initial series of 70 coals. The majority of the 20 coals were low in pyritic sulfur and little improvement could be

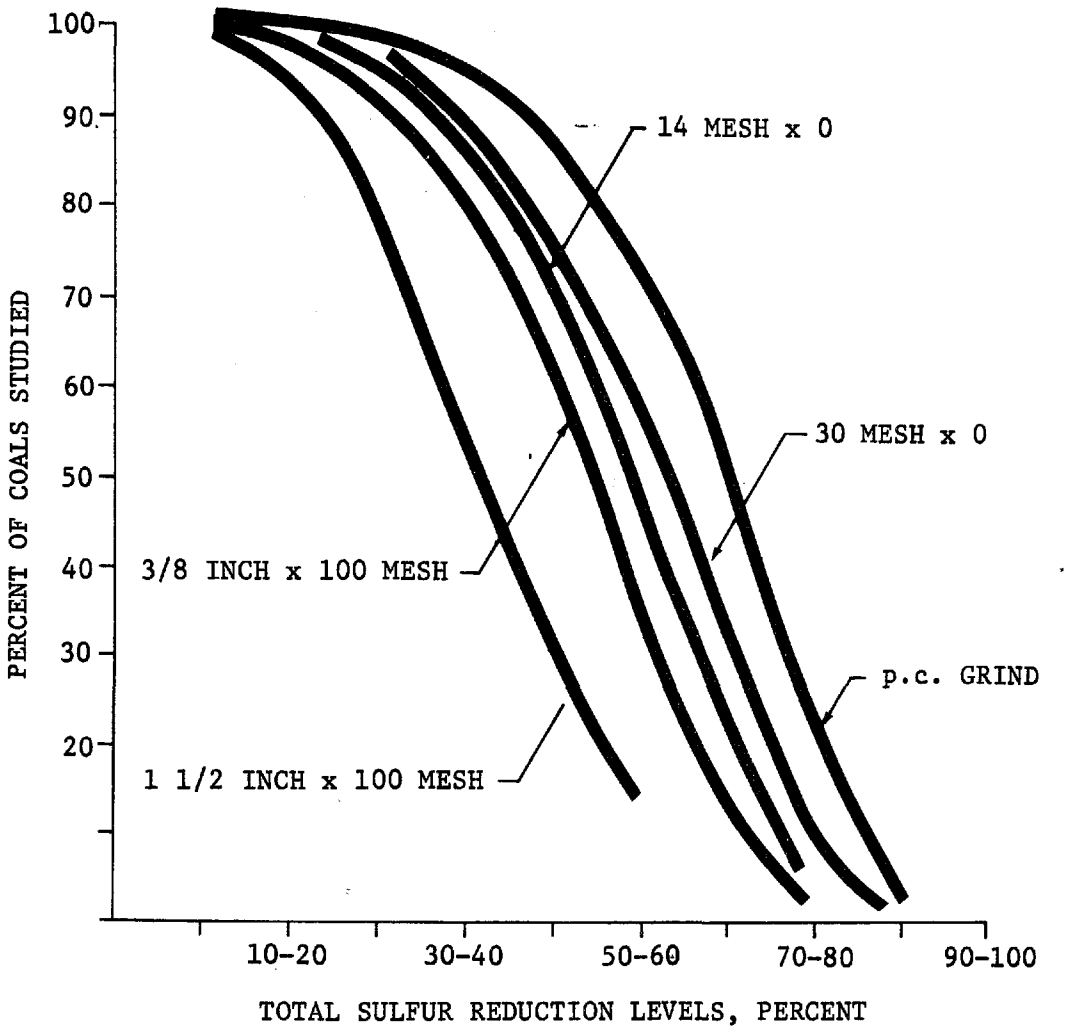
made in sulfur reduction regardless of top size crushing. The majority of the group, high in pyritic sulfur, were also high in organic sulfur. Consequently, total reductions were not overly impressive.

The washability results of the first series of 70 coals and the second series of 20 coals are provided in Figures 18 and 19, respectively. These figures show the total sulfur reduction at 1.60 float for R.O.M. coal crushed to the following sizes: 3/8-inch x 100 mesh, 14 mesh x 0, 30 mesh x 0, and p.c. grind. Figure 18 shows that for the initial 70-coal series, the maximum total sulfur reduction ranged from 50 to 60 percent for 10 of the coals at the 1 1/2 inch top size to 80 to 90 percent for one coal at the p.c. grind. This figure indicates that the largest incremental sulfur reduction is obtained when the coal is reduced in size from a 1 1/2 inch top size to a 3/8 inch top size.

Figure 19, covering the second series of 20 coals, shows that at the 1 1/2 inch top size 25 percent of the coals tested (five coals) could be reduced in total sulfur by 20 to 30 percent when washed at a 1.60 specific gravity. In addition, five percent of the coals (i.e., one coal) did not change in sulfur content when its top size was reduced from 14 mesh to 30 mesh. The highest obtained total sulfur reduction was 69 percent with one coal at its p.c. grind; indicating the fineness of the pyrite distribution in this coal.

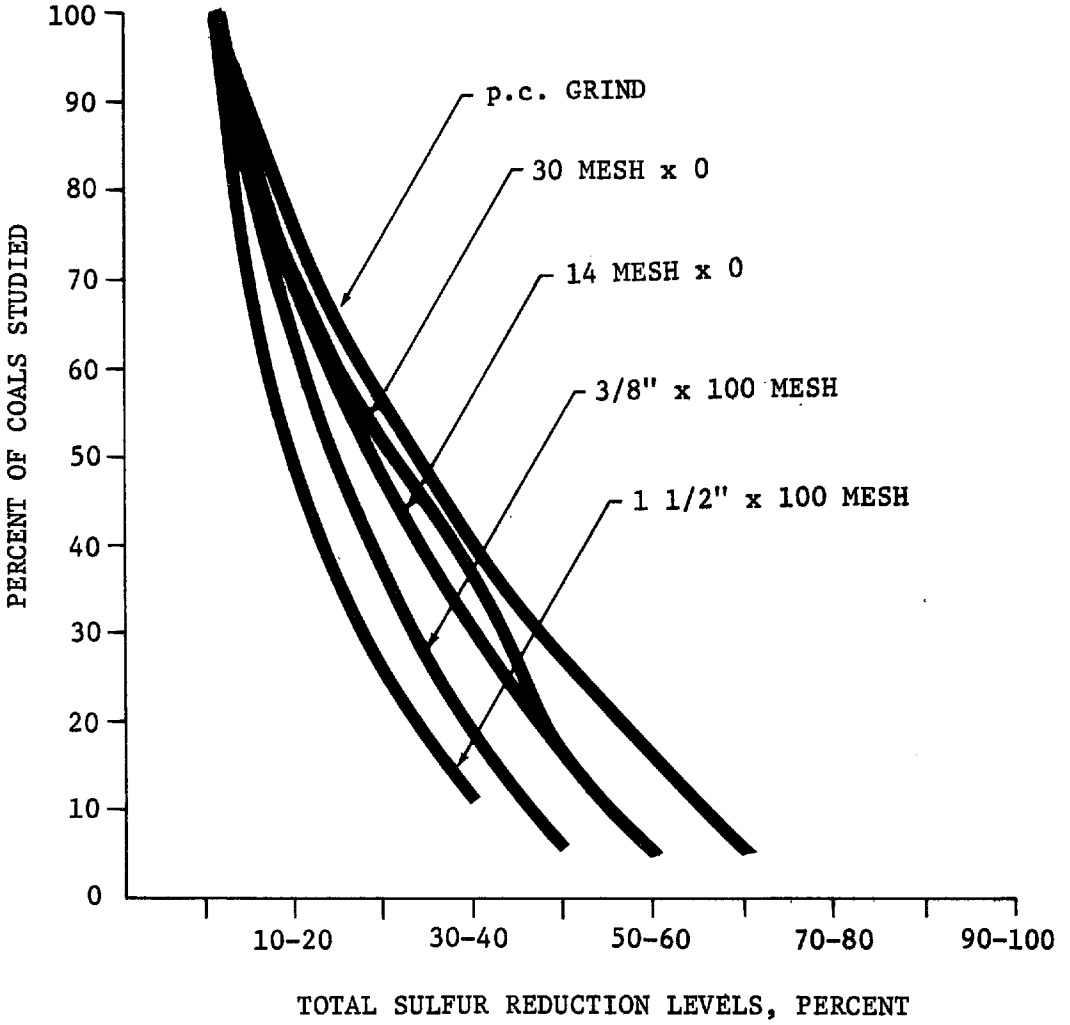
4.4.8 Comparability of Core Samples and Face Samples[11]

One of the specific objectives of the (Phase II) Illinois Geological Survey effort was to ascertain whether useful washability data could



SOURCE: REFERENCE 6

FIGURE 18
TOTAL SULFUR REDUCTION AT 1.60 SPECIFIC GRAVITY AS RELATED TO SIZE FOR 70 W. PENNSYLVANIA, E. OHIO, AND ILLINOIS COALS



SOURCE: REFERENCE 10

FIGURE 19
TOTAL SULFUR REDUCTION AT 1.60 SPECIFIC GRAVITY AS RELATED TO SIZE FOR 20 SOUTHERN, WESTERN, AND MID-WESTERN COALS

be obtained from 2-inch-diameter core samples by examining the correlations between this size sample and the normal size (i.e., large) sample. Since these core samples usually weighed 10 pounds (approximately 6 foot seam thickness), washability tests were made on both the 10-pound core samples and the 100-pound fractions from normal face samples taken in the same approximate locations.

Table IV lists the percentages of total sulfur, pyritic sulfur, and ash for 40, 60, and 80 percent recoveries for the 23 normal samples covering this effort. Also shown are the corresponding values for the tests made on the small (core) samples (Suffix S). The differences between the values given for the large and small samples are usually less than those specified by ASTM for analytical tolerance between laboratories.

Figures 20 and 21 illustrate the similarity of results with large and small samples. The curves are considered as the best fit for the data obtained with the large samples. The deviation from the curves of the data points for the small sample are considered minor.

TABLE IV

COMPARISON OF WASHABILITIES OF SMALL AND LARGE SAMPLES

	40 percent recovery			60 percent recovery			80 percent recovery		
	Sulfur (%)		Ash	Sulfur (%)		Ash	Sulfur (%)		Ash
Sample*	Total	Pyritic	%	Total	Pyritic	%	Total	Pyritic	%
1	3.21	0.44	4.2	3.32	0.56	5.4	3.51	0.81	7.3
1S	3.29	0.53	4.2	3.30	0.57	5.2	3.45	0.79	7.0
2	2.46	0.42	2.4	2.57	0.58	3.4	2.80	0.87	5.5
2S	2.50	0.51	2.9	2.56	0.58	3.4	2.77	0.84	5.5
3	2.39	0.49	2.8	2.55	0.66	3.8	2.90	1.01	6.1
3S	2.40	0.49	2.5	2.55	0.64	3.4	2.85	0.94	5.4
4	2.81	0.55	6.1	2.91	0.65	6.5	3.22	0.96	7.5
4S	2.96	0.65	5.6	3.03	0.73	6.1	3.30	1.00	7.0
5	1.85	0.75	3.6	2.24	1.10	5.0	2.84	1.67	6.9
5S	1.88	0.89	4.2	2.02	1.09	5.1	2.51	1.64	6.9
6	0.81	0.17	3.4	0.85	0.22	4.3	0.93	0.31	5.5
6S	0.84	0.20	3.4	0.87	0.23	4.1	0.94	0.32	5.4
7	1.62	0.36	2.9	1.74	0.48	4.1	1.91	0.65	6.0
7S	1.64	0.40	2.8	1.78	0.50	4.0	1.95	0.67	5.9
8	2.40	0.43	2.3	2.49	0.52	3.2	2.67	0.71	4.9
8S	2.42	0.42	2.4	2.51	0.53	3.3	2.66	0.70	5.0
9	2.77	0.56	3.5	2.88	0.67	4.3	3.08	0.85	5.7
9S	2.66	0.56	3.3	2.75	0.65	4.1	2.94	0.86	5.5
10	1.99	0.44	3.0	2.06	0.55	4.1	2.21	0.73	6.0
10S	1.93	0.44	3.2	1.99	0.52	3.9	3.15	0.71	6.0
11	1.92	0.45	2.1	2.04	0.63	3.8	2.35	0.95	6.6

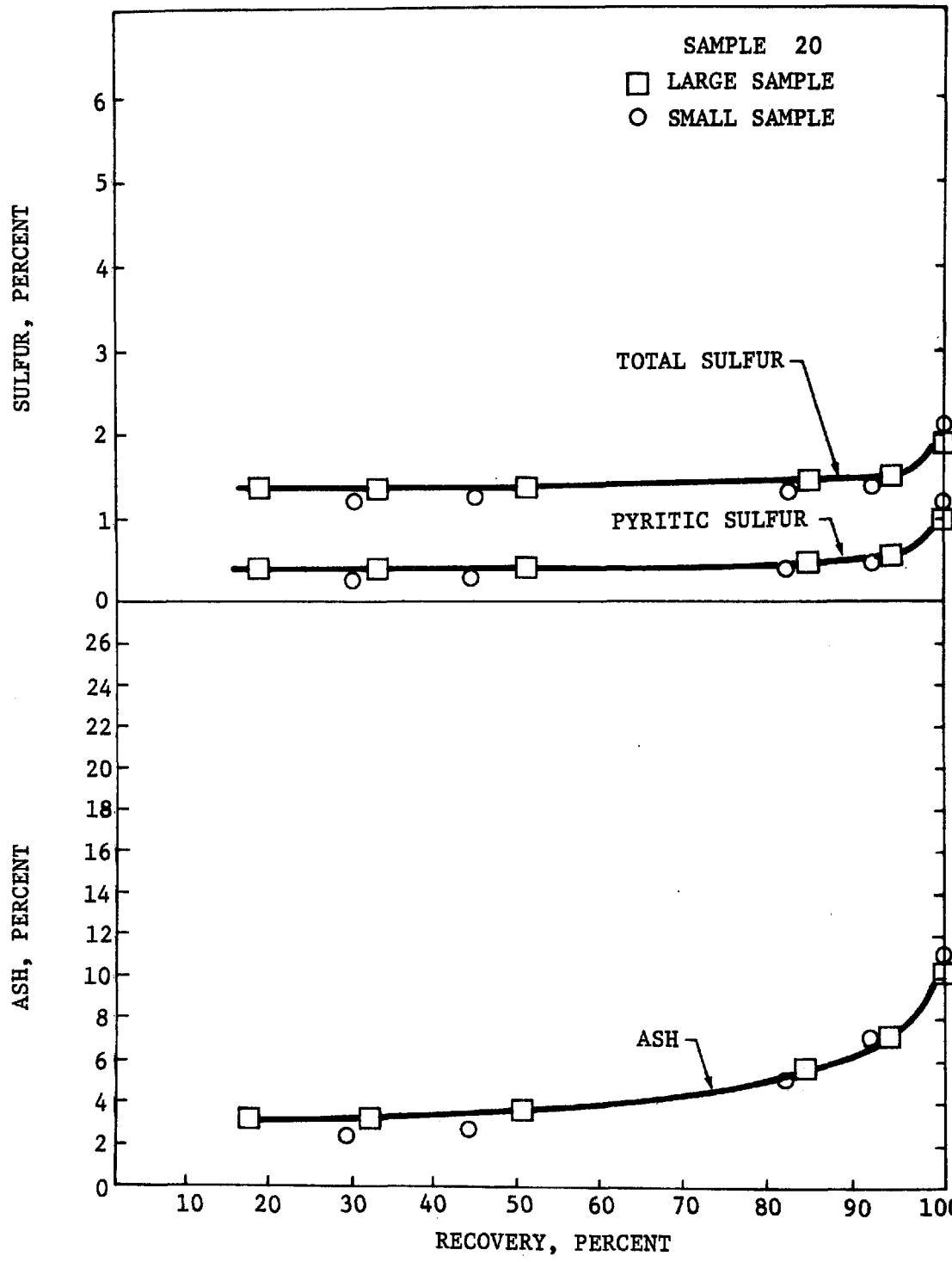
* S = test run on small sample

TABLE IV (con't)

COMPARISON OF WASHABILITIES OF SMALL AND LARGE SAMPLES

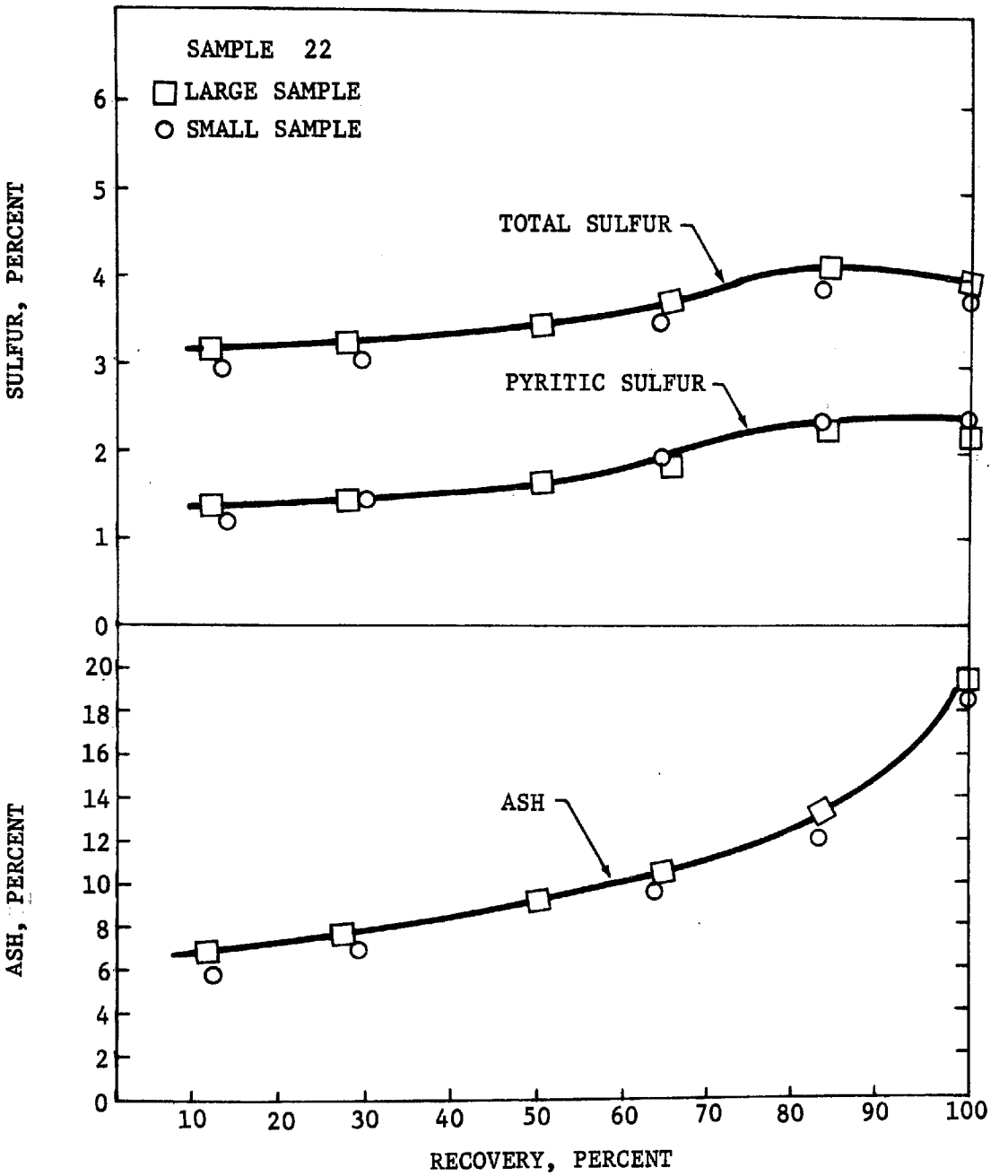
	40 percent recovery			60 percent recovery			80 percent recovery		
*	Sulfur (%)		Ash	Sulfur (%)		Ash	Sulfur (%)		Ash
Sample	Total	Pyritic	%	Total	Pyritic	%	Total	Pyritic	%
11S	2.08	0.47	3.3	2.13	0.56	4.5	2.39	0.87	6.8
12	1.76	0.72	4.5	1.86	0.84	5.5	2.07	1.08	6.9
12S	1.78	0.76	4.8	1.82	0.83	5.6	1.97	1.04	6.9
13	2.59	0.33	2.9	2.75	0.48	4.4	2.93	0.66	6.8
13S	2.75	0.60	3.9	2.80	0.66	4.6	3.01	0.92	7.4
14	0.71	0.15	3.5	0.71	0.17	4.1	0.72	0.19	4.7
14S	0.70	0.12	3.5	0.70	0.12	4.0	0.70	0.15	4.6
15	0.53	0.02	3.0	0.53	0.02	3.6	0.57	0.07	4.6
15S	0.57	0.08	3.2	0.57	0.08	3.8	0.58	0.08	4.7
16	2.07	0.45	4.5	2.24	0.67	5.9	2.59	1.04	7.6
16S	2.20	0.54	4.6	2.34	0.67	6.0	2.63	1.02	7.7
17	3.14	0.48	4.1	3.16	0.53	4.7	3.36	0.79	6.3
17S	3.38	0.46	4.0	3.43	0.52	4.7	3.62	0.76	6.2
18	2.49	0.71	3.0	2.68	0.87	4.3	2.93	1.13	6.6
18S	2.77	0.89	4.1	2.91	1.02	5.1	3.08	1.22	7.0
19	2.56	0.51	3.1	2.71	0.69	4.5	2.95	1.02	6.8
19S	2.66	0.63	4.2	2.71	0.70	4.8	2.91	0.97	6.9
20	1.37	0.41	3.1	1.41	0.43	3.9	1.48	0.50	5.5
20S	1.25	0.33	2.4	1.32	0.38	3.3	1.39	0.47	5.3
21	2.21	0.32	6.0	2.23	0.36	7.0	2.26	0.42	8.6
21S	2.26	0.34	7.0	2.26	0.34	7.2	2.29	0.41	8.6
22	3.39	1.57	8.4	3.68	1.87	10.2	4.07	2.31	12.6
22S	3.30	1.61	8.0	3.57	1.92	9.9	3.94	2.33	12.3
23	3.81	0.38	3.7	3.85	0.54	4.9	4.07	0.90	6.8
23S	3.82	0.43	4.1	3.82	0.52	5.1	4.02	0.86	7.0

Source: Reference 11.



SOURCE: REFERENCE 11

FIGURE 20
WASHABILITY CHARACTERISTICS OF SAMPLE 20



SOURCE: REFERENCE 11

FIGURE 21
WASHABILITY CHARACTERISTICS OF SAMPLE 22

5.0 LABORATORY AND PILOT STUDIES EVALUATING PROCESSES FOR PYRITE REMOVAL FROM FINE COALS

This section describes the EPA-sponsored laboratory and pilot study projects conducted by the Bureau of Mines and Bituminous Coal Research, Incorporated. The objectives were (1) to determine the operating parameters for maximum pyrite separation, (2) to modify existing techniques and/or develop new techniques to separate pyrite from fine coals, and (3) to evaluate methods to process coal cleaning rejects so as to concentrate the pyrite and reclaim clean coal products.

The equipment or processes were evaluated by the two contractor organizations as indicated below. The Bureau of Mines efforts concentrated on equipment operational parameters and the development of new techniques while the Bituminous Coal Research efforts concentrated on the applicability of equipment to various coals.

	Investigated by	
Equipment/Process	Bureau of Mines	Bituminous Coal Research, Inc.
Wet Concentrating Table (Deister)	X	X
Concentrating Spiral (Humphry)	X	X
Hydrocyclones	X	X
Air Classifiers		X
Electrokinetic Techniques	Y	
Agglomo-Separation	X,Y	
Froth Flotation	X,Y	

X designates pilot plant tests

Y designates laboratory-scale tests

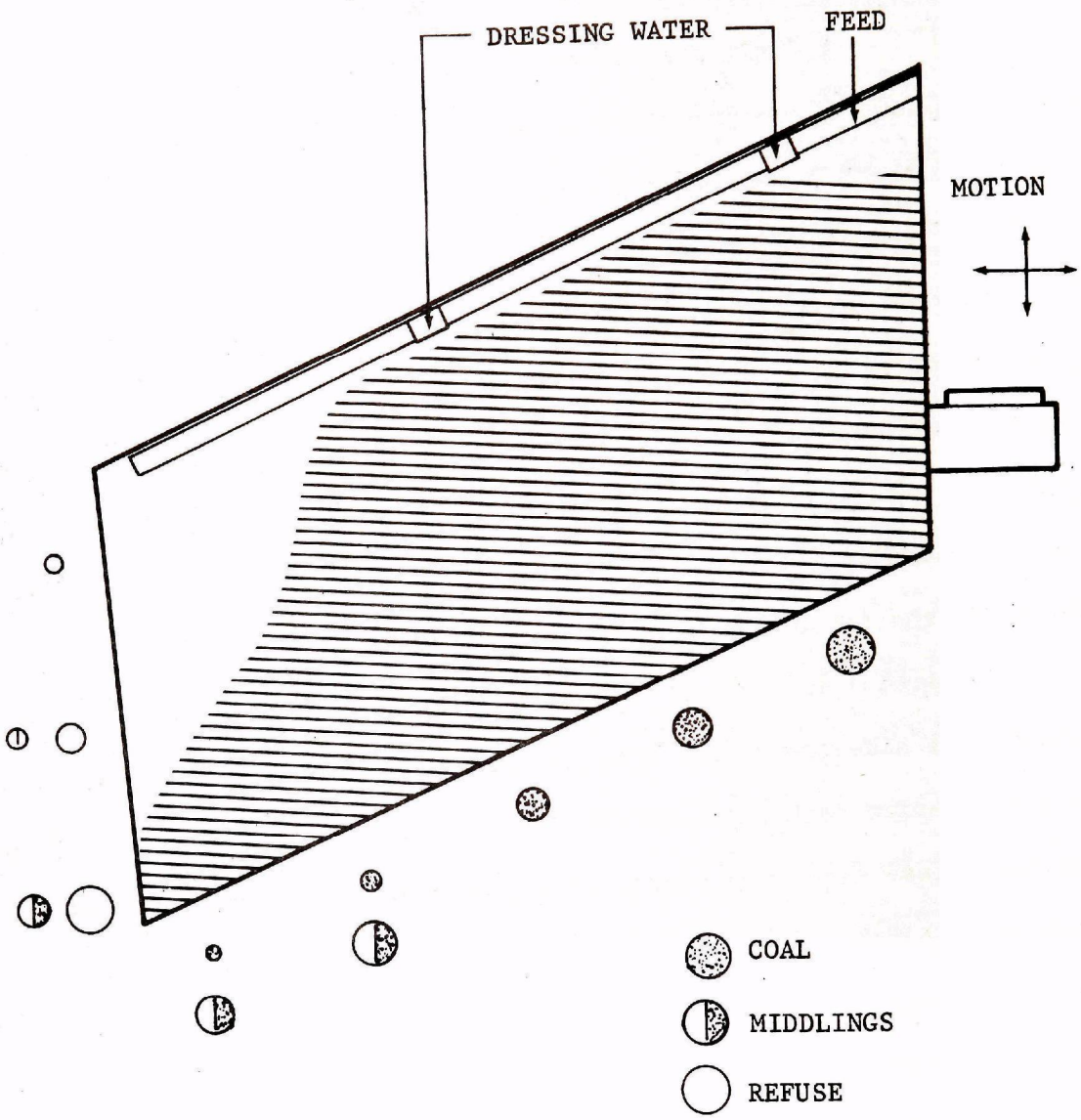
These processes are described briefly in the following sections and results of their performance are summarized.

5.1 Wet Concentrating Table

The wet table is a rectangular or rhomboid-shaped normally riffled deck operated in essentially a horizontal plane. A drive mechanism imparts a differential motion to the deck along its long axis while water flows by gravity along the short axis of the table. The rapid shaking motion causes particles of different densities to migrate to different zones on the table's periphery.

Commercial tables have a deck approximately 16 feet long on the clean coal side and 8 feet long on the refuse side. In these studies, a quarter-size deck, 8 feet long on the clean coal side and 4 feet long on the refuse side, was used. The direction of the feed coal mixture and the reporting of the clean coal, middlings, and refuse to the various sections of the table are shown in Figure 22. As the specific gravity of the coarse particles increases, the material deposits further around the table toward the refuse end.

In tests by the Bureau of Mines and Bituminous Coal Research, Incorporated, the wet concentrating table proved effective in separating liberated pyrite and ash from coal. Coals with a high proportion of pyritic sulfur relative to organic sulfur are particularly amenable to sulfur reduction by this process.



SOURCE: REFERENCE 12

FIGURE 22
DISTRIBUTION OF CLEAN COAL, MIDDLINGS, AND REFUSE ON THE WET CONCENTRATING TABLE

Two series of wet concentrating table tests were performed by the Bureau of Mines, one on a normal size table feed and the second on a rather fine size feed. The results of cleaning minus 1/4 inch coal are shown in Table V. The pyritic sulfur content was reduced from 3.07 to 0.60 percent and the total sulfur from 3.63 to 1.20 percent at a clean coal recovery of 86.3 percent.

Further analyses on the coal (first series of tests) were made by screening the minus 1/4 inch coal into four size fractions as indicated by Table V. The combined pyritic sulfur reduction for the three larger size fractions was approximately 84 percent each. Also, the efficiency of the separation deteriorated in the minus 200 mesh size range where the pyritic sulfur reduction was only 58 percent.

For the Bureau's second series of tests (Table VI) conducted on 35 mesh x 0 size coal, the 35 by 200 mesh fraction shows the pyritic sulfur content reduced by 75 percent, from 2.05 percent in the feed to 0.50 percent in the clean coal. The pyritic sulfur in the minus 200 mesh by 0 size fraction was reduced by 23 percent, or from 1.69 percent in the feed to 1.30 in the clean coal.

The results of the second series of wet concentrating table tests are shown in Table VI. When the sample was broken down into the plus and minus 200 mesh size fractions, the results showed that the efficiency of the table for separating pyrite from coal deteriorated below the 200 mesh size range.

TABLE V

PRODUCT ANALYSIS OF A 1/4 INCH BY 0 SIZE COAL WASHED ON A WET CONCENTRATING TABLE

Products	Percent			
	Weight	Ash	Pyritic Sulfur	Total Sulfur
		1/4 inch by 14 mesh, 41.6 percent		
Clean coal	87.3	2.6	0.56	1.13
Refuse	12.7	36.9	19.19	19.60
Feed	100.0	7.0	2.92	3.47
		14 by 48 mesh, 38.9 percent		
Clean coal	86.1	2.6	.45	1.08
Refuse	13.9	40.9	17.15	17.66
Feed	100.0	7.9	2.77	3.38
		48 by 200 mesh, 15.2 percent		
Clean coal	83.8	5.9	.56	1.17
Refuse	16.2	68.0	17.69	17.79
Feed	100.0	15.8	3.32	3.85
		200 mesh by 0, 4.3 percent		
Clean coal	86.1	28.4	2.51	3.08
Refuse	13.9	71.9	27.51	27.64
Feed	100.0	34.6	6.00	6.51
		1/4 inch by 0, 100.0 percent		
Clean coal	86.3	4.2	.60	1.20
Refuse	13.7	45.6	18.49	18.86
Feed	100.0	9.9	3.07	3.63

Source: Reference 12.

TABLE VI

PRODUCT ANALYSIS OF A 35 MESH BY 0 SIZE
COAL WASHED ON A WET CONCENTRATING TABLE

Product	Percent			
	Weight	Ash	Pyritic sulfur	Total sulfur
		35 by 200 mesh, 63.9 percent		
Clean coal	63.7	8.7	0.50	1.25
Refuse	36.3	53.2	4.77	5.18
Feed	100.0	24.8	2.05	2.67
		200 mesh by 0, 36.1 percent		
Clean coal	92.4	16.1	1.30	1.98
Refuse	7.6	27.6	6.51	7.08
Feed	100.0	17.0	1.69	2.36
		35 mesh by 0, 100.0 percent		
Clean coal	74.0	12.0	.87	1.58
Refuse	26.0	50.5	4.95	5.39
Feed	100.0	22.0	1.92	2.56

Source: Reference 12.

In addition to the above, two-stage cleaning tests, in which a coarse sample (3/8 inch x 0) was tabled on a quarter sized unit and the clean fraction pulverized to a finer size (30 mesh x 0) which was re-tabled, were performed by Bituminous Coal Research. Equipment for testing the coarse sample had a capacity of 2-1/2 to 3 tons per hour, and that for the fine sample of 1 to 1-1/4 tons per hour. These tests indicated that pyrite removal can be improved by use of the concentration table in two stages. A total of eight coals, five eastern and three (mid)western, were subjected to two-stage tabling. These coals are identified and their sulfur contents are shown in Table VII. The results are given in Table VIII which also shows feed rate during testing, percent total sulfur in the feed, and percent sulfur in clean coal. Reductions in total sulfur range from 29 percent to 68 percent.

5.2 Concentrating Spiral

The concentrating spiral, although widely used for ore dressing, has never been used for coal preparation even though it had been previously considered for coal cleaning purposes. It was evaluated because of its low capital and operating costs.

The concentrating spiral (see Figure 23) consists of a spiral conduit of modified semicircular cross section. In operation, pulp is fed from the top of the spiral and as it flows downward centrifugal force causes the heavier particles to concentrate in a band along the inner side of the spiral. They are removed through adjustable ports

TABLE VII
ANALYSIS OF COALS SELECTED FOR CONCENTRATING TABLE TESTS

Coal Identification Seam County, State	BCR Lot No.	Weight Percent, Dry Basis					Organic Sulfur as Percent of Total Sulfur
		Ash	Total Sulfur	Sulfate Sulfur	Pyritic Sulfur	Organic Sulfur	
Eastern Coals							
No. 6-A Harrison, Ohio	1735	10.4	2.50	0.01	1.86	0.63	25.2
Upper Freeport Westmoreland, Pa.	1750	22.5	3.74	0.03	3.22	0.49	13.1
No. 8 Jefferson, Ohio	1768	19.4	4.71	0.07	3.69	0.95	20.2
No. 6 Columbiana, Ohio	1745	10.4	2.44	0.05	1.79	0.60	24.6
Lower Kittanning Indiana, Pa.	1755	20.1	4.66	0.05	4.00	0.61	13.1
Midwestern Coals							
Lower Cherokee	2415	12.8	5.12	0.26	4.24	0.62	
Upper Spandra	2416	6.5	1.59	0.08	0.77	0.74	
Tebo Seam	2417	29.8	6.92	0.68	4.44	1.80	

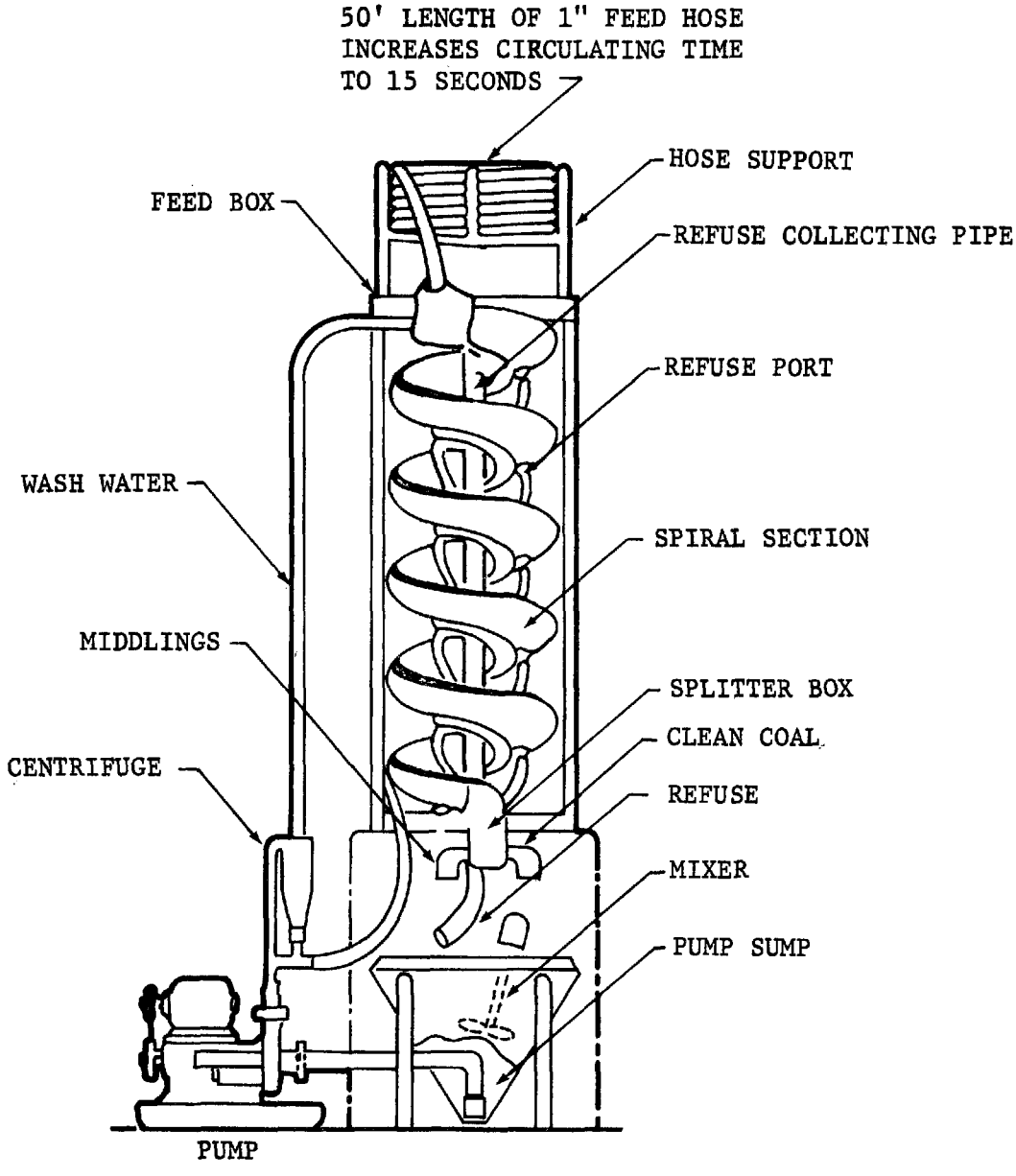
Adapted from References 6 and 10.

TABLE VIII
CONCENTRATING TABLE TESTS
EFFECT OF TWO-STAGE CLEANING

Coal Identification Seam County State	BCR Lot No.	Feed Size	Feed Rate tph	Total Sulfur, Feed to Table* (Percent)	Recovery, Clean Coal (Percent)	Total Sulfur, Clean Coal (Percent)	Total Sulfur Reduction (Percent)
Eastern Coals							
No. 6-A	1950	3/8 in x 0	2.39	2.82	91.8	2.12	24.8
Harrison, Ohio	1950	30 Mesh x 0	1.13	--	87.5**	1.40	50.4
Upper Freeport	2012	3/8 in x 0	2.66	3.34	84.9	1.76	47.3
Westmoreland, Pa.	2012	30 Mesh x 0	1.09	--	81.4**	1.07	68.0
No. 8	2013	3/8 in x 0	2.85	3.83	92.4	3.29	14.1
Jefferson, Ohio	2013	30 Mesh x 0	.99	--	87.4**	2.72	29.0
No. 6	2026	3/8 in x 0	2.62	4.38	94.4	2.57	41.3
Columbiana, Ohio	2026	30 Mesh x 0	1.00	--	90.7**	1.65	62.3
Lower Kittanning	2031	3/8 in x 0	2.55	4.77	83.5	1.98	58.5
Indiana, Pa.	2031	30 Mesh x 0	.82	--	78.8**	1.54	67.7
Midwestern Coals							
Lower Cherokee	2415	3/8 in x 0		***	89.3	3.53	33.7
		30 Mesh x 0			95.5**	3.14	42.8
Upper Spadra	2416	3/8 in x 0		***	96.4	1.21	24.7
		30 Mesh x 0			96.5**	0.97	40.5
Tebo Seam	2417	3/8 in x 0		***	77.6	4.57	42.9
		30 Mesh x 0			93.9**	4.29	50.8

* Composite of Table Product
** Based on 100 percent 3/8 inch x 0 raw coal feed.
*** See Table VII for approximation

Source: Adapted from References 6 and 10.



SOURCE: REFERENCE 12

FIGURE 23
HUMPHREYS SPIRAL CONCENTRATOR CLOSED CIRCUIT TEST UNIT

located on each turn of the spiral at the lowest point in the cross section of the conduit. As the spiral stream is discharged from the lower end of the spiral, an adjustable splitter divides the stream into two products: a clean coal product (outer coal) and a middling product (inner coal).

The Bureau of Mines evaluated spiraling on coals of top sizes ranging from 4 mesh down to 35 mesh and on double sized fractions. It was found that the best separation occurred when the top size of the spiral feed was minus 14 mesh or less. Surprisingly, the capacity of the spiral remained about constant, regardless of the feed top size. Consequently, the capacity of the spiral for washing fine-size coal was very high.

The results of spiraling 35 mesh by 0 Middle Kittanning bed coal are shown in Table IX. A feed coal having a total sulfur content of 2.53 percent was reduced to 1.48 percent by spiraling at a clean coal recovery of 90.7 percent. The final sulfur content of the washed 35 by 200 mesh coal was 0.92 percent sulfur, while the sulfur content of the washed minus 200 mesh coal was 2.34 percent sulfur. This rapid deterioration of the efficiency of the washing technique with size reduction is a normal characteristic of specific gravity separators. The excellent results achieved by the Bureau of Mines with the spiral on fine-size coal suggest it should be considered along with hydrocyclones and the wet concentrating tables as a "rougher" cleaning unit to remove pyrite from high sulfur coals prior to flotation.

TABLE IX

PRODUCT ANALYSIS OF 35 MESH BY 0 MIDDLE KITTANNING BED COAL WASHED OVER THE COAL SPIRAL

	Percent			
Product	Weight	Ash	Pyritic Sulfur	Total Sulfur
	35 by 200 mesh, 62.2 percent of feed			
Clean coal	88.3	7.2	0.29	0.92
Refuse	11.7	42.8	13.51	13.79
Feed	100.0	11.4	1.85	2.43
	200 mesh by 0, 37.8 percent of feed			
Clean coal	94.7	12.0	1.71	2.34
Refuse	5.3	21.4	8.48	8.96
Feed	100.0	12.5	2/07	2.69
	Composite 35 mesh by 0, 100.0 percent of feed			
Clean coal	90.7	9.1	.86	1.48
Refuse	9.3	38.2	12.43	12.75
Feed	100.0	11.8	1.94	2.53

Source: Reference 12.

Five different coals were used by Bituminous Coal Research, Inc., in their evaluation of the concentrating spiral for cleaning coal. These coals were from the following seams:

1. No. 6-A seam, Harrison County, Ohio
2. Lower Kittanning seam, Indiana County, Pennsylvania
3. No. 6 seam, Columbiana County, Ohio
4. Upper Freeport seam, Westmoreland County, Pennsylvania
5. No. 8 seam, Jefferson County, Ohio.

Their sulfur contents are given in Table VII. Coal from the No. 6-A Ohio seam was tested at the 30 mesh x 0 size, while the other four were precleaned on the wet concentrating table at the 3/8 inch x 0 size and the clean-coal fraction then crushed to 30 mesh x 0. The fine coal was then cleaned on the spiral.

A 15.3 percent reduction in total sulfur, 94.8 percent recovery, was obtained by single stage cleaning of the 30 mesh x 0, Ohio 6-A seam coal. This result was obtained by combining the screen fractions of the middling material and the clean coal. For both the single and double-stage cleaning, it was found that all the clean coal fractions contained a significant quantity of high-ash, high-sulfur sink material. Results of the double-stage cleaning appear in Table X. Comparison of these sulfur reductions with those obtained by cleaning the same coals with the wet concentrating table (Table VIII) indicate that the spiral produces similar reductions and yields for two of the coals tested and somewhat lower reductions for the other two.

TABLE X
CONCENTRATING TABLE AND SPIRAL CONCENTRATOR TESTS
EFFECTS OF TWO-STAGE CLEANING

Coal Identification Lot	Seam	Location County, State	Total Sulfur, Feed to Table* Percent	Clean Coal, Two-stage Cleaning Percent	Total Sulfur Reduction, Two-stage Cleaning Percent
2031	Lower Kittanning	Indiana, Pennsylvania	3.66	78.3	65.3
2026	No. 6	Columbiana, Ohio	2.90	89.3	48.3
2012	Upper Freeport	Westmoreland, Pennsylvania	3.30	77.9	54.5
2013	No. 8	Jefferson, Ohio	3.98	87.0	28.4

* Based on Composite of Table Products, Rough Cleaning

Source: Reference 6.

5.3 Water Cyclone

Water cyclone performance evaluation tests were conducted by the Bureau of Mines on five units in commercial plants. Preliminary results of these tests showed excellent pyritic sulfur reductions were attainable. The clean coal recoveries were highly dependent on the size of the material. Clean coal recovery of the plus 48 mesh material was low, while most of the minus 100 mesh material reported to the clean coal product. Final results of this work are planned to be published in a Bureau of Mines report entitled Performance Characteristics of Coal-Washing Equipment: Water-Only Cyclones.

Water cyclone tests were also conducted by Bituminous Coal Research, Inc.[6, 10] Feed coals were pulverized to minus 30 mesh size prior to test runs. Ohio 6-A seam coal was used in the first set of tests. For the remaining four tests, feed material was prepared by pulverizing the minus 3/8 inch clean fraction from the concentrating table to minus 30 mesh. This approach is analogous to the two-stage cleaning with the concentrating table.

In two-stage cleaning of the minus 30 mesh Ohio 6-A coal, the total sulfur was reduced from 2.90 to 1.59 percent (ref. Table XI). A comparison of the compound water cyclone run with the concentrating table run is shown in Table XII. This table indicates that the concentrating table performed better than the compound water cyclone in the cleaning of this coal. This finding is supported by the results of cyclone-

TABLE XI

COMPARISON OF CONCENTRATING TABLE RUNS AND COMPOUND WATER CYCLONE RUN WITH 30 MESH X 0, R.O.M., OHIO NO. 6-A SEAM

Cleaning Unit	Total Sulfur in Feed, Weight Percent	Recovery, Weight Percent	Total Sulfur Reduction, Weight Percent
Compound Water Cyclone (Test No. 3, Run No. 6)	2.47	91.4	21.1
Compound Water Cyclone (Test No. 2, Run No. 2)	2.39	90.9	27.6
Concentrating Table Run	2.44	92.0	36.5

Source: Reference 6.

TABLE XII
CONCENTRATING TABLE AND COMPOUND WATER CYCLONE TESTS
EFFECTS OF TWO-STAGE CLEANING

Run No. 2 Operating Conditions

Coal Identification Lot	Seam	Location County, State	Total Sulfur Feed to Table* Percent	Clean Coal Two-stage Cleaning Percent	Total Sulfur Reduction, Two-stage Cleaning Percent
2031	Lower Kittanning	Indiana, Pennsylvania	3.66	73.2	57.9
2026	No. 6	Columbiana, Ohio	2.90	80.3	44.8
2012	Upper Freeport	Westmoreland, Pennsylvania	3.30	69.9	62.7
2013	No. 8	Jefferson, Ohio	3.98	78.8	34.7

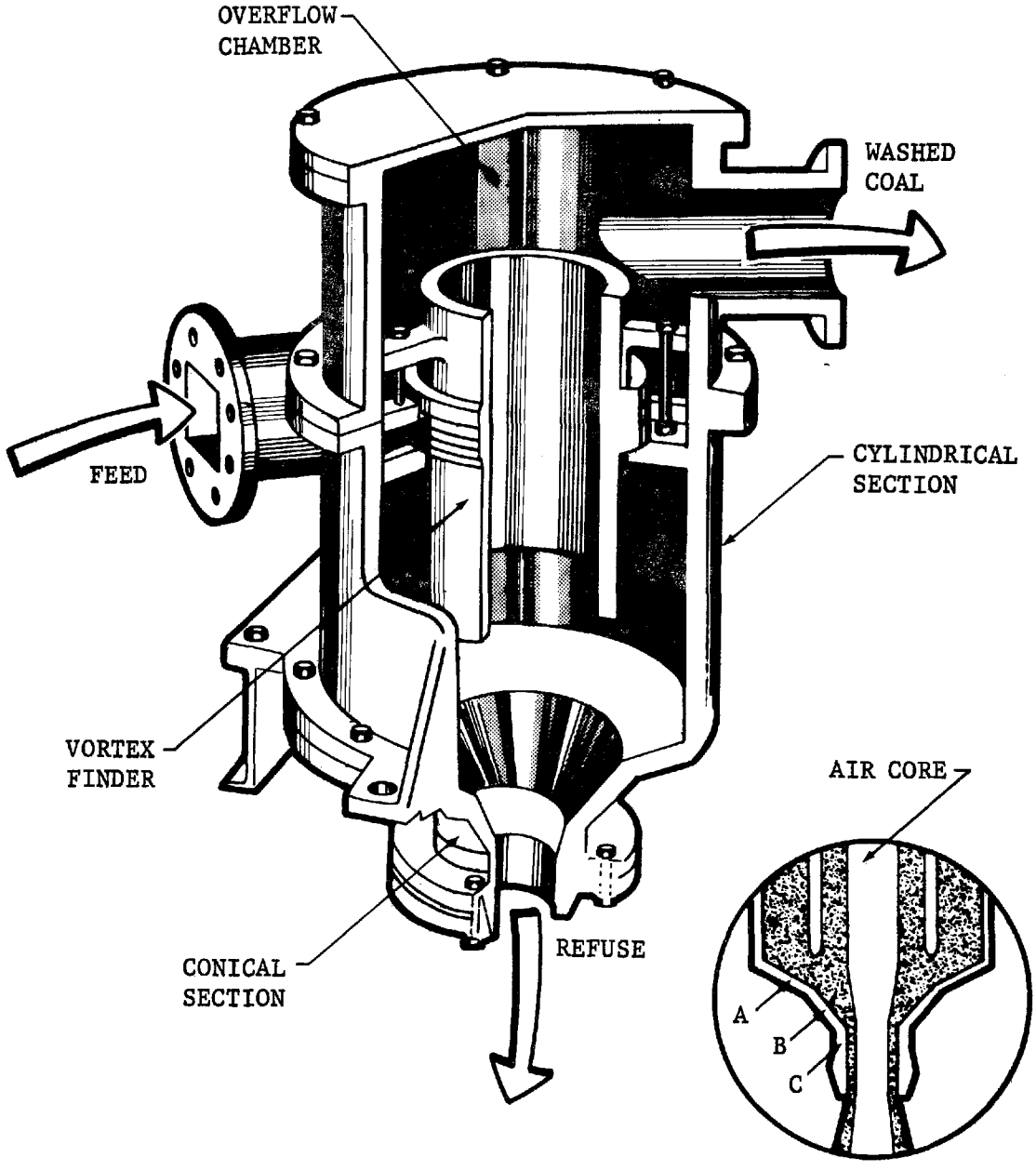
*Based on Composite of Table Products, Rough Cleaning.

Run No. 2 Operating Conditions:
Cone Type "M", Vortex Finder Clearance: 1", Inlet Pressure: 8 psi, Feed Solids Concentration: 8.0%.

Source: Reference 6.

cleaning the other four coals (at 30 mesh x 0 size) which had been pre-cleaned on the concentrating table. Table XI gives results under one set of test conditions. These tests show smaller sulfur reductions for three of the four coals tested than were achieved by the wet concentrating table (Table VIII). Bituminous Coal Research, Inc. believes that improved results in total sulfur reduction could have been obtained by using a closer-sized feed or feeds to the compound water cyclone, i.e., 30 mesh x 200 mesh and 200 mesh x 0[6].

A diagram of a McNally Visman Tricone of the type evaluated by Bituminous Coal Research, Inc., is shown in Figure 24. It consists of a cylindrical section, a compound conical section and a vortex finder. In operation, coal/water tangentially enters near the top of the cylindrical section, forming a strong vertical flow. Refuse moves along the wall of the cyclone and is discharged through the apex. The washed coal passes through the vortex finder to the overflow chamber. Washed coal is discharged from this chamber through the tangential outlet. This particular design of the water-only cyclone has three conical sections. Particles of different sizes and specific gravities form a hindered settling bed in the first conical section. Light coarse particles are removed from the first conical section (A) and light middlings are removed from (B) the second conical section. In the last conical section (C), the bed is destroyed and the heavy fractions pass through the apex. The central current of the departing water is weak at this point and



ADAPTED FROM REFERENCE 6.

FIGURE 24
COMPOUND WATER CYCLONE

only the fine, light particles are discharged through the vortex finder.

5.4 Air Classifier

This is a two-stage process. First air is used to separate the relatively coarse grind of pulverized coal into a fine fraction and a coarse, pyrite-rich fraction using the BCR-Majac and Alpine zigzag air classifiers. Pyrite can then be removed from the coarse fraction by wet-coal preparation techniques.

Float-and-sink analyses at 1.60 specific gravity were conducted on both the coarse and fine fractions. The composite of the coarse and fine clean coal fractions were also analyzed.

Ten samples from the group of coals used for float-sink washability studies were selected for testing. (Note that this group is not from the same sample lots as used for testing other types of cleaning equipment; e.g., the spiral.) The reduction of total sulfur by use of the Majac unit ranged from 20.1 to 51.7 percent. The results of the ten coals are given in Table XIII. One coal was also processed on the Alpine Zigzag unit (Table XIV).

5.5 Electrokinetics

The electrokinetic process for the physical cleaning of coal use the technique of electrophoresis for separating the pyrite from the coal. Electrophoresis is defined as the migration of electrokinetically charged particles in a liquid toward an electrode of opposite charge in

TABLE XIII
PYRITIC SULFUR REDUCTION IN MAJAC AIR CLASSIFICATION TESTS

BCR Lot No.	Seam	Total Sulfur in Raw Coal Percent	Pyritic Sulfur in Raw Coal, Percent	Recovery Majac Product Percent	Total Sulfur in Majac Product Percent*	Total Sulfur Reduction Percent	Pyritic Sulfur in Majac Product* Percent	Pyritic Sulfur Reduction, Percent
1752	Upper Kittanning	2.71	2.31	90.4	1.31	51.7	0.94	59.3
1750	Upper Freeport	3.74	3.22	83.6	1.98	47.1	1.48	54.0
1771	Lower Freeport	2.54	1.89	92.6	1.49	41.3	0.98	48.1
1745	No. 6	2.44	1.79	94.3	1.46	40.2	1.01	43.6
1770	Thick Freeport	2.08	1.68	90.9	1.25	39.1	0.92	45.2
1735	No. 6-A	2.50	1.86	93.2	1.65	34.0	0.98	47.3
1730	No. 6	4.72	3.70	92.2	3.16	33.1	2.17	41.4
1747	Lower Kittanning and Lower Freeport	2.42	1.84	90.7	1.65	31.8	1.08	41.3
1757	Freeport	2.52	2.16	77.5	1.90	24.6	1.39	35.6
1733	No. 8	4.58	2.84	87.6	3.66	20.1	1.95	31.3

* Majac product composed of raw fine coal plus cleaned coarse fraction (1.60 specific gravity)

Source: Reference 6.

TABLE XIV
SULFUR REDUCTION IN ALPINE ZIGZAG CLASSIFIER TESTS

A--Total Sulfur Reduction

BCR Lot No.	Seam	Rank	Total Sulfur in Raw Coal, Percent	Zigzag Product, Percent	Total Sulfur in Zigzag Product,* Percent	Total Sulfur Reduction, Percent
1733	No. 8	HVC	4.58	84.1	3.82	16.6

* Zigzag product composed of raw fine coal plus cleaned coarse fraction (1.60 specific gravity)

B--Pyritic Sulfur Reduction

BCR Lot No.	Seam	Rank	Pyritic Sulfur in Raw Coal, Percent	Zigzag Product, Percent	Pyritic Sulfur in Zigzag Product,** Percent	Pyritic Sulfur Reduction, Percent
1733	No. 8	HVC	2.84	84.1	1.90	33.1

** Zigzag product composed of raw fine coal plus cleaned coarse fraction (1.60 specific gravity)

Source: Reference 6.

a d-c electrical field. The speed of migration is directly proportional to the magnitude of the electrokinetic charge of the particles and the applied voltage and inversely proportional to the distance between the electrodes. The electrokinetic process was investigated on a laboratory scale.

The application of electrophoresis to physically wash coal was based on earlier studies which showed that, while coal and pyrite were both negatively charged above a pH of 4, the coal was more negatively charged than the pyrites. In the use of the electrophoretic technique for the separation of pyrites from coal, however, it was found that the electrophoretic mobilities of coal and pyrite were never sufficient to overcome the effects of the specific gravity and the size variance in particles. Therefore, a modified cell was built to take into account not only the electrophoretic mobilities of coal and pyrite, but also their specific gravities (described in Reference 13).

The electrophoretic cell consisted of a rectangular plastic column with inside dimensions of 3/8 inch by 3/8 inch by 24 inches. Platinum electrode wires were used to produce a d-c field. The column was longitudinally inclined at an angle of 45 degrees and laterally inclined at angles varying from 4 to 11 degrees. The anode was located on the high side of the laterally inclined column and the cathode was on the lower side. During operation, the coal slurry was fed into the top of the column and, as the slurry moved down the length of the column with an applied d-c field, the heavier and less negatively charged pyrites

tended to slide toward the cathodic side and the coal was drawn toward the anode.

Initial tests were conducted with the electrophoresis column using synthetic coal-pyrite mixtures. Next, a series of tests were conducted on a high-pyritic-sulfur coal. Results of three test runs are given in Table XV.

The laboratory-scale investigation indicated that this was an effective method to remove pyrite and other impurities such as silica from coal. Economic assessments, unfortunately, indicated that the technique would be too costly for commercial application. Therefore further development was not pursued. The electrophoresis column could probably best be used as a laboratory instrument for investigating the physical desulfurization of coal.

5.6 Agglomo-Separation (Oil)

The Agglomeration-Separation process developed by the National Research Council of Canada was investigated by the Bureau of Mines. The process was reported to recover a product low in ash approaching the clean coal product. It was felt that a similar sulfur reduction might be obtained. In addition, the process had the capability to agglomerate fine size coal to a larger size and eventually to provide for pelletization.

High energy mixing is employed to disperse kerosine or similar light oils in a coal-water slurry. The oil selectively coats the coal particles causing the particles to agglomerate and then, with an assist

TABLE XV

FRACTIONATION OF A SAMPLE OF 100 BY 325 MESH LOWER FREEPORT BED COAL IN AN ELECTROPHORESIS COLUMN

TEST	APPLIED VOLTAGE VOLTS, DC	AVERAGE CURRENT MILLIAMPS	RECEPTACLE	RECOVERY, PERCENT	ASH, PERCENT	PYRITIC SULFUR, PERCENT	TOTAL SULFUR, PERCENT
1	500	5.0	Coal	94.3	13.2	1.01	1.61
			Reject	5.7	45.0	19.73	19.95
2	400	2.0	Coal	55.6	17.0	.34	1.07
			Reject	44.4	14.8	4.63	5.58
3	250	1.5	Coal 1st pass	13.8	44.5	.38	.61
	500	5.0	Coal 2nd pass	77.3	8.9	.62	1.38
			Reject	8.9	44.8	21.00	22.65

Source: Reference 12.

from entrained air, rise to the surface, while the impurities remain in the water. The investigation was conducted on both 35 mesh x 0 and 325 mesh x 0 sized coals using kerosine as the agglomerating oil in slurries containing 10 percent of coal by weight. Experiments were conducted on both the laboratory and bench scale. A blender-type mixer was used in the laboratory experiments, and a 4-gallon cell was used for bench-scale testing.

Four variables; kerosine dosage, retention time, slurry pH, and mixer speed were evaluated in the laboratory. Kerosine dosage had the most significant effect. Generally, a concentration of 8 percent kerosine, based on the weight of dry coal in the slurry, produced the best results. At lower kerosine levels the recovery of clean coal decreased, while using larger amount of kerosine provided minimal increases in recovery of clean coal. Increasing the retention time from 1 to 2 minutes increased recovery. Beyond 2 minutes, however, there was no increase in recovery. Neither the pH of the slurry nor the speed of mixing had a significant effect on the product recovery.

Tables XVI and XVII show the results of two samples of 325 mesh x 0 size coals evaluated in the laboratory. Reductions in total sulfur range from about 12 percent to 39 percent while yields of clean coal range from 18 percent to 85 percent, depending on test conditions and the type of coal. Under the same conditions ash reduction ranges from 25 percent to 60 percent.

TABLE XVI

EVALUATION OF THE AGGLOMO-SEPARATION PROCESS FOR THE LOWER FREEPORT BED COAL USING FOUR PROCESS VARIABLES

Coal Size	Minus 325 mesh
Total Sulfur, percent	2.5
Ash, percent	19.3
Agglomerating Oil	Kerosine
Slurry, percent solids	10

TEST NO.	KEROSINE DOSAGE, PERCENT	AGITATOR SPEED, RPM	RETENTION TIME, MIN.	SLURRY pH	CLEAN COAL PERCENT YIELD	SULFUR	ASH
1	2	10,000	1	6.0	58.5	1.9	12.8
2	4	10,000	1	6.0	70.5	2.2	11.2
3	8	10,000	1	6.0	81.8	2.1	11.2
4	2	10,000	2	6.0	60.4	2.0	12.8
5	4	10,000	2	6.0	75.0	1.9	11.2
6	8	10,000	2	6.0	82.5	2.2	10.5
7	2	10,000	1	10.0	68.5	1.9	12.1
8	4	10,000	1	10.0	78.5	1.9	12.0
9	8	10,000	1	10.0	82.1	2.1	10.1
10	2	10,000	2	10.0	77.4	1.8	10.0
11	4	10,000	2	10.0	81.5	2.0	8.7
12	8	10,000	2	10.0	82.7	2.2	9.2
13	2	14,000	1	6.0	62.0	1.8	11.6
14	4	14,000	1	6.0	70.1	1.9	11.6
15	8	14,000	1	6.0	82.6	2.1	10.6
16	2	14,000	2	6.0	70.3	1.8	10.6
17	4	14,000	2	6.0	75.4	1.9	12.3
18	8	14,000	2	6.0	83.9	2.0	9.2
19	2	14,000	1	10.0	68.6	1.7	10.7
20	4	14,000	1	10.0	76.3	2.0	11.9
21	8	14,000	1	10.0	85.0	2.1	9.3
22	2	14,000	2	10.0	74.5	1.8	10.2
23	4	14,000	2	10.0	78.5	1.9	8.8
24	8	14,000	2	10.0	83.6	2.1	8.5

Source: Reference 14.

TABLE XVII

EVALUATION OF THE AGGLOMO-SEPARATION PROCESS FOR THE PITTSBURGH BED COAL USING FOUR PROCESS VARIABLES

Coal Size	Minus 325 mesh
Total Sulfur, percent	2.3
Ash, percent	16.1
Agglomerating Oil	Kerosine
Slurry, percent solids	10

Test no.	Kerosine dosage, percent	Agitator speed, rpm	Retention time, min.	Slurry pH	Clean Coal Percent yield	sulfur	ash
25	2	6,000	1	3.0	18.1	1.7	10.9
26	4	6,000	1	3.2	54.1	1.6	11.7
27	8	6,000	1	2.9	60.4	1.7	9.9
28	2	6,000	2	3.1	17.1	1.5	8.8
29	4	6,000	2	3.0	49.5	1.7	10.5
30	8	6,000	2	3.0	63.5	1.7	10.0
31	2	6,000	1	10.0	39.8	1.8	12.0
32	4	6,000	1	10.0	54.5	1.6	11.0
33	8	6,000	1	10.0	65.8	1.8	10.6
34	2	6,000	2	10.0	36.3	1.6	10.7
35	4	6,000	2	10.0	53.3	1.8	10.5
36	8	6,000	2	10.0	60.6	1.6	9.0
37	2	12,000	1	3.2	35.9	1.7	9.7
38	4	12,000	1	3.1	52.9	1.7	9.8
39	8	12,000	1	3.4	68.1	1.7	10.1
40	2	12,000	2	3.0	24.4	1.4	8.0
41	4	12,000	2	3.1	48.8	1.6	9.7
42	8	12,000	2	3.2	64.7	1.6	10.3
43	2	12,000	1	10.0	40.1	1.6	10.8
44	4	12,000	1	10.0	53.4	1.6	10.2
45	8	12,000	1	10.0	62.6	1.6	9.0
46	2	12,000	2	10.0	42.3	1.5	10.3
47	4	12,000	2	10.0	56.3	1.7	10.7
48	8	12,000	2	10.0	67.5	1.4	9.0

Source: Reference 14.

The agglomo-separation process provided only limited sulfur reduction but a substantial reduction in ash. The oil coats the pyrite as well as the coal particles, resulting in agglomerates containing both the clean coal and the pyrite. There is usually some sulfur reduction accompanying low recoveries of clean coal due to low concentrations of agglomerating oil but, as the oil concentration is increased to obtain maximum clean coal recovery, the percentage of sulfur in the product is usually equal to or greater than that of the raw coal.

The laboratory work was scaled up to a 500 pound per hour pilot plant consisting of two 4-gallon capacity cells equipped with turbine blade impellers, a Bird dewatering screen bowl centrifuge, and a Dravo 39 inch pelletizing disc. With this arrangement, a 10 percent slurry of 35 mesh x 0 size coal was agglomerated with 8 percent kerosine. The agglomerated clean coal was dewatered to about 16 percent moisture content in the centrifuge and then pelletized on the disc-pelletizer using an asphalt binder. This step was performed to study pelletization as a means of overcoming some of the problems encountered in drying and handling fine-sized coals. Pellets made with approximately 5 percent asphalt binder averaged 1/2 inch in diameter and contained about 16 percent moisture. The pellets were firm when wet and had good strength and water resistance when dried.

The quality of the clean coal produced by the pilot plant was similar to that obtained in the laboratory unit. The sulfur reduction was negligible, but the recovery of low ash coal was good.

5.7 Froth Flotation

"Froth flotation is a process for separating fine-size particles by selective attachment of air bubbles to coal particles, causing them to be buoyed up into a froth while leaving the refuse particles in the water. This process deals with fine particles in a rather turbulent and foamy aqueous system where specific gravity is not as significant as the surface properties of the particles; although much heavier than the coal, due to surface characteristics the pyrite remains with the coal in the froth product"[12].

The process consists of thoroughly mixing the fine raw coal particles with water. A frothing agent is added, and air is bubbled through the mixture, causing a froth to be produced at the surface. This froth, containing primarily the hydrophobic components, is skimmed away, thereby separating the hydrophobic from the hydrophilic fractions which remain suspended in the bulk of water. The froth flotation process is reasonably new for coal processing, although it has long been used in the mineral industry to effect separations between various minerals often of a very complex nature.

The research program to determine the pyrite reduction potential of the froth flotation process pursued two approaches. These are 1) the depression of coal, and 2) the depression of pyrite. The depression of pyrite approach, involving a one-stage process, was not encouraging. The detailed procedures, results, and conclusions are presented in Reference 15.

The second approach was concerned with a two-stage flotation process for separating the pyrite remaining in the "initial" froth flotation product. This product from a conventional single-stage flotation process is repulped in fresh water; treated with a coal flotation depressant, a pyrite collector, and a frother; and is rewashed in a second bank of froth flotation cells. The pyrites are removed with the froth, leaving a depressed fraction of clean coal containing less pyrites. This two-stage process can be reversed, i.e., the pyrite is floated (and the coal is depressed) in the first stage and the coal is conventionally floated in the second stage. The two-stage froth flotation process was developed because in the one-stage process the fine-sized pyrites reported with the froth product. Work on the two-stage flotation process in a half ton per hour capacity pilot plant has been completed.

Detailed results of the froth flotation research are presented in Tables XVIII and XIX and in References 15 and 16. A more complete description of the process may be found in References 12 and 17.

Of the innovative processes for pyrite separation investigated by the Bureau of Mines under the EPA Clean Coal Program, the two-stage froth flotation technique appears to show the greatest potential for scale-up to commercial operation. The importance of this process results from the fact that no other way has been identified to remove pyrite from fine coals.

TABLE XVIII

TWO-STAGE FLOTATION RESULTS WITH LOWER FREEPORT BED COAL SLURRY

Product	Weight, percent	Analysis, percent: Ash	Analysis, percent: Total sulfur	Analysis, percent: Pyritic sulfur	Distribution, percent: Ash	Distribution, percent: Total sulfur	Distribution, percent: Pyritic sulfur
Test 1: First stage; 40 g/ton MIBC Second stage; 250 g/ton Aero Depressant 633, 150 g/ton potassium amyl xanthate, 40 g/ton MIBC							
Clean coal 2	64.2	10.0	1.11	0.51	22.2	30.8	20.5
Reject 2	9.1	15.5	7.06	6.54	4.9	27.8	37.2
Clean coal 1	73.3	10.7	1.85	1.26	27.1	58.6	57.7
Reject 1	26.7	79.8	3.57	3.51	72.9	41.4	42.3
Feed	100.0	28.9	2.31	1.60	100.0	100.0	100.0
Test 2: First stage; 40 g/ton MIBC Second stage; 500 g/ton Aero Depressant 633, 200 g/ton potassium amyl xanthate, 40 g/ton MIBC							
Clean coal 2	63.5	9.3	1.03	.46	20.4	28.8	16.2
Reject 2	8.1	17.0	7.93	7.35	4.8	28.3	33.1
Clean coal 1	71.6	10.2	1.81	1.24	25.2	57.1	49.3
Reject 1	28.4	76.2	3.43	3.22	74.8	42.9	50.7
Feed	100.0	28.9	2.27	1.80	100.0	100.0	100.0
Test 3: First stage; 40 g/ton MIBC Second stage; 350 g/ton Aero Depressant 633, 250 g/ton potassium amyl xanthate, 40 g/ton MIBC							
Clean coal 2	59.7	9.8	.94	.32	20.4	24.3	10.4
Reject 2	12.7	13.4	5.84	5.06	5.9	32.1	35.1
Clean coal 1	72.4	10.4	1.80	1.15	26.3	56.4	45.5
Reject 1	27.6	77.2	3.61	3.60	73.7	43.6	54.5
Feed	100.0	28.7	2.31	1.83	100.0	100.0	100.0

Source: Reference 14.

TABLE XIX

TWO-STAGE FLOTATION RESULTS WITH MIDDLE KITTANNING BED COAL SLURRY

Product	Weight Percent	Analysis, Percent: Ash	Total Sulfur	Pyritic Sulfur	Distribution, Percent: Ash	Total Sulfur	Pyritic Sulfur
Test 1: First stage; 300 g/ton kerosine, 80 g/ton MIBC							
Second stage; 250 g/ton Aero Depressant 633, 150 g/ton potassium amyl xanthate, 40 g/ton MIBC							
Clean coal 2	74.5	3.2	1.22	0.69	32.2	31.6	21.9
Reject 2	10.1	5.6	3.23	2.68	7.6	11.3	11.5
Clean coal 1	84.6	3.5	1.46	.93	39.8	42.9	33.4
Reject 1	15.4	28.8	10.65	10.18	60.2	57.1	66.6
Feed	100.0	7.4	2.88	2.35	100.0	100.0	100.0
Test 2: First stage; 300 g/ton kerosine, 80 g/ton MIBC							
Second stage; 350 g/ton Aero Depressant 633, 250 g/ton potassium amyl xanthate, 40 g/ton MIBC							
Clean coal 2	76.1	2.7	.95	.33	27.4	25.2	10.6
Reject 2	9.0	10.5	6.22	6.22	12.6	19.5	23.5
Clean coal 1	85.1	3.5	1.51	.95	40.0	44.7	34.1
Reject 1	14.9	30.1	10.68	10.53	60.0	55.3	65.9
Feed	100.0	7.5	2.87	2.38	100.0	100.0	100.0
Test 3: First stage; 300 g/ton kerosine, 80 g/ton MIBC							
Second stage; 500 g/ton Aero Depressant 633, 350 g/ton potassium amyl xanthate, 40 g/ton MIBC							
Clean coal 2	78.8	2.6	.89	.34	30.1	24.4	11.4
Reject 2	9.9	12.2	7.83	7.23	17.8	27.0	30.5
Clean coal 1	88.7	3.7	1.66	1.11	47.9	51.4	41.9
Reject 1	11.3	31.7	12.30	12.13	52.1	48.6	58.1
Feed	100.0	6.8	2.87	2.35	100.0	100.0	100.0

Source: Reference 14

5.8 Concentration of Pyrite from Refuse

The laboratory and pilot studies discussed above have been concerned primarily with removing sulfur, principally in the form of pyrite, from coal. Similar, though less extensive, studies were performed by Bituminous Coal Research, Inc., to determine the potential of fine-cleaning techniques for preparing a concentrated grade of pyrite from the reject material[10]. These investigations were undertaken because most of the major commercial processes for conversion of pyritic sulfur to sulfuric acid or other usable forms require a pyritic feedstock considerably richer in pyrite than the reject material produced by physically cleaning most U.S. bituminous coals.*

Coals from six mines, with total sulfur content ranging from about 1.1 to 6.9 percent, were cleaned and the reject concentrated by staged separation with wet concentrating tables and a hydraulic classifier. For this effort, samples of each coal were crushed to 3/8 inch x 0, and pre-cleaned on a wet concentrating table of the type normally used for coal preparation. The fraction with the highest specific gravity (presumably containing most of the pyrites) was crushed to 30 mesh x 0 and cleaned on a metallurgical-type wet concentrating table with slime deck.

*Conventional processes that burn pyrites and produce sulfuric acid require ore with a minimum sulfur content of about 42 percent. Total sulfur in the refuse from high-sulfur coals varies from about 4 to 25 percent. Therefore, if this refuse is to be a suitable feed for acid production, it must be concentrated to a higher pyrite grade. Also, see Section 7.2.

This was considered as concentrated pyrite. The fraction having the next-to-highest specific gravity was crushed to 60 mesh x 0 and re-cleaned on the metallurgical deck. In some cases, an intermediate separation of the 60 mesh x 0 material was made with a hydraulic classifier prior to the second cleaning on the metallurgical deck. The hydraulic classifier was not used for all tests because of the high percentage of fine pyrite lost during this operation.

Results are summarized in Table XX. These indicate that pyrite concentrates with sufficiently high total sulfur content for conventional acid-making processes can be achieved for all coals tested, but sometimes at the expense of percentage of sulfur recovered. Total sulfur in the pyrite concentrates range from 35.6 percent (corresponding to a recovery of 46 percent of total sulfur in the ROM coal) to 48.6 percent (corresponding to a 22.9 percent recovery).

The effort verified that pyrite from refuse can be concentrated for use as a feedstock for the recovery of sulfur values in either the form of elemental sulfur or sulfuric acid. The processing of rejects from various cleaning processes offers the capability to recover coal values and to adjust the feedstock composition to the requirements of a specific pyrite utilization process such as the High Sulfur Combustor (covered in Section 8.0).

TABLE XX
SULFUR RECOVERY IN PURITE CONCENTRATION TESTS

Coal Identification	Total Sulfur, R.O.M. Coal, Percent	Pyritic Sulfur, R.O.M. Coal, Percent	Percent of Sulfur in R.O.M. Coal Reclaimed in Pyrite Concentrate		Total Sulfur, Pyrite Concentrate Percent	Ultimate Carbon, Percent
			Total Sulfur	Pyritic Sulfur		
2234 Ohio No. 6	3.19	2.56	22.9	28.5	48.59	3.63
2255 Upper Kittanning	2.02	1.72	46.0	54.1	35.64	4.84
2287 Indiana VII	1.06	0.39	3.8	10.3	44.07	2.93
2299 Lower Freeport	2.82	2.07	18.1	24.6	45.96	4.45
2415 Lower Cherokee	5.12	4.24	13.1	15.8	44.70	5.46
2417 Tebo	6.92	4.44	12.3	19.1	47.18	3.51
Averages	3.52	2.57	19.4	25.4	44.36	

Source: Reference 10.

6.0 PROTOTYPE COAL CLEANING PLANTS

The washability studies and pilot plant investigations previously discussed indicated the amenability of a wide range of coals to physical desulfurization under carefully controlled laboratory conditions. Quite different results could be obtained from the same types of coal cleaning equipment when operating in the laboratory than when operating in commercial-scale plants where conditions may be less carefully controlled and where variability in the feed composition may be greater. Although testing for pyrite removal could be conducted to a limited degree in some existing preparation plants, the equipment and cleaning circuits of such plants are not normally arranged to maximize sulfur reduction but to meet ash and BTU specifications. Commercial cleaning plants are usually designed for maximum effectiveness in cleaning a specific coal and do not have the flexibility of cleaning equipment and circuits to maximize sulfur reduction of different coals having widely varying washability characteristics. For this reason, testing in existing plants would be difficult and generally unsatisfactory without extensive modification to equipment and circuits.

Ideally, a plant to be used for investigating and demonstrating desulfurization methods at high through-put capacities would provide flexibility of equipment configurations, cleaning circuits, and operating conditions to permit adaptability to the desulfurization requirements of the various coals to be processed and to provide for maximum pyrite recovery from the refuse. The plant must have the proper sampling

and laboratory arrangements so that the coals and equipment can be properly evaluated. Such a plant would ideally be situated in a location central to the coals to be tested and the plant site should contain ground space available for a possible future plant for processing the pyrite recovered from the refuse.

In order to determine the scope and cost of conducting investigations and demonstrations of pyrite removal using commercial cleaning equipment on a scale approximating commercial capacity, EPA funded two independent and competitive studies for designing a prototype coal cleaning plant of 50-100 tons per hour capacity and for estimating the capital and operating cost for the plant. (Ref. 18, 19, 20, 21). Testing laboratories were addressed in the cost estimates. Due to plant and related operational complexities and associated costs, two independent and competitive studies were needed for EPA to identify the most acceptable design/cost option.

The study objectives were to produce a prototype plant design capable of reducing the sulfur of various coals having widely variable washability characteristics and other physical and chemical properties together with providing cost estimates for building and equipping the plant and for performing appropriate studies on selected coals. Specific elements of the task were:

- To review and analyze the coal washability data furnished by EPA;
- To develop a ranking of the coals and select those most appropriate for evaluation in the prototype plant;

- To develop a design with circuits that could optimize sulfur reduction from a variety of coals;
- To select the most appropriate plant location;
- To develop detailed installed cost of the prototype plant;
- To develop a test plan and schedule for evaluating each selected coal; and
- To develop detailed costs for operating the plant, conducting the tests, and analyzing the generated data.

The prototype plant design and cost studies were conducted by the Roberts and Schaefer Company of Chicago and the McNally Pittsburg Manufacturing Corporation, Pittsburg, Kansas. Each of these organizations analyzed the washability data for some 200 coals, classified the coals relative to amenability to physical desulfurization, designed a prototype plant for sulfur removal, and developed the required test plans and cost estimates.

The major difference in the two studies was plant design; Roberts and Schaefer's design was the more complex of the two, however, it offered the maximum flexibility; the McNally design was the less complex and provided reduced flexibility and greater ease of operation. In view of the wide variation in coals to be tested, the provided maximum flexibility would more than off-set the probable resulting incremental operating difficulties. Results of the two independent studies are summarized in the following sections.

6.1 Classification and Selection of Coals

Both study efforts (i.e., McNally Pittsburg and Roberts & Schaefer) reviewed and analyzed the coal washability data provided by EPA. Each study effort examined the washability data on approximately 200 coals, from various parts of the United States, to identify coals that potentially would benefit from cleaning by achieving a significant reduction in sulfur content. Each study effort developed a coal grouping by size, sulfur content of the washed coal, coal recovery values, and coal type with region of origin.

The Robert and Schaefer effort considered as candidates those coals for which cleaning could yield substantial benefits. The criteria used for selecting candidate coals were:

- Sulfur content in the raw coal should be relatively high;
- The proportion of pyritic sulfur in the raw coal should be relatively high;
- Significant reduction in total sulfur should be possible at commercially feasible yields (i.e., greater than 65 percent);
- Sulfur reduction should be judged in relation to geographic area or coal field considered;
- Substantial reserves of coal should be available;
- Consideration should be given to coals which appear difficult to clean;
- Consideration should be given to selecting candidates from different geographic locations; and

- Candidates should be selected according to the sulfur level in the clean coal and should cover the following ranges: less than 1 percent, 1.0-1.5 percent, 1.5-2.0 percent, and 2.0-2.5 percent total sulfur.

Based on the above criteria, 32 coals were initially identified with the decision to select four additional candidates at a later date.

The McNally Pittsburg effort identified 46 coals considered to have good or fair washability characteristics. These 46 coals were characterized as being cleanable to less than 1.5 percent total sulfur and deserving testing in the proposed coal cleaning plant. These were composed of 20 coals in excess of 1 percent sulfur that would wash to less than 1 percent sulfur with a recovery in excess of 75 percent, 26 coals that would either wash to less than 1 percent sulfur with a 50 to 75 percent recovery, or those that would wash to 1 to 1.5 percent sulfur with a 75 to 100 percent recovery.

The differences in the numbers of coals selected by the two contractors, i.e., Roberts and Schaefer and McNally Pittsburg is due to differences in selection criteria and yields. Roberts and Schaefer limited their selections to coals providing commercial acceptable yields of 65 percent or more whereas McNally Pittsburg considered yields down to 50 percent. In addition, the two contractors had different criteria for acceptable total sulfur in the clean coal.

6.2 Design of Roberts and Schaefer Prototype Cleaning Plant, Test Plan, and Costs[18, 19, 20]

6.2.1 Roberts and Schaefer Plant Design

The Roberts and Schaefer plant design concept is flexible with alternate circuits and equipment choices which can be run in various combinations so as to handle coals of different sizes and widely varying washability characteristics. The Roberts and Schaefer proposed plant design comprises the following:

1. Heavy medium cyclone. Two stages of heavy medium cyclones are provided in the prototype plant. The primary stage is for low-gravity and is fed by gravity. The second stage is for higher gravities and is fed by pumping.
2. Hydrocyclones. Two stages of 20-inch-diameter hydrocyclones are used for cleaning 3/8 inch x 0 coal. The hydrocyclones are used for their flexibility in varying the specific gravity (1.40 - 1.80). In addition, fourteen-inch-diameter hydrocyclones will be available to clean 1/2 mm x 0 raw coal.
3. Deister table. The Deister table is used for 3/8 inch x 0 and 1/2 mm x 100 mesh sized coal cleaning.

The equipment selection is based not only on the ability of each type to clean coals at low specific gravities but also the relative efficiency of each. The following equipment was excluded because of lack of ability to clean coal at low specific gravities: fine coal jig, air table, hydrotator, and the rheolaveur.

In addition, the plant would contain a complete complement of equipment for receiving, storing, handling, crushing, sizing, sampling, testing, drying, and transporting of coal and reject material, plus utilities and instrumentation. The facility would also include office space, a fully equipped chemical laboratory for analysis work, and data processing equipment needed to interface with a leased computer.

The test plant is designed for a maximum capacity of 75 TPH. This maximum capacity will be maintained while the heavy medium cyclones and the 20-inch-diameter hydrocyclones are in use. When the Deister tables are in use using a raw feed of 1/4 or 3/8 inch top size, the plant capacity is reduced to 50 TPH. The plant capacity is also limited to 50 TPH when raw coal is pulverized to 14 mesh x 0. For preparing the 14 mesh x 0 size, the pulverizing and cleaning equipment for treating 1/2 mm x 0 are the limiting factors for plant feed capacity.

Specifics concerning the plant and processes are as follows. Two heavy medium cyclone circuits are furnished; a primary heavy medium cyclone circuit and a secondary heavy medium cyclone circuit. Three products are generated from these two circuits: the low sulfur content clean coal, the high sulfur content middlings, and the refuse. The primary heavy medium reject is rinsed out on a reject screen. The discharge of the screen can be fed into the secondary circuit directly or be crushed, deslimed, and then fed to the secondary circuit.

The raw coal feed to the heavy medium cyclone circuit will be either 1-1/2 inch or 3/8 inch top size. If the raw coal is 1-1/2 inch x 0 size,

it will by-pass the raw coal screen and will be delivered with water via raw coal pump to the desliming sieve bend and screen for removing the 1/2 mm x 0 fines. The plus 1/2 mm raw coal will be fed to the primary heavy medium cyclone, and the 1/2 mm x 0 will be directed to the 1/2 mm x 0 sump for subsequent cleaning. When the 1-1/2 inch x 0 raw coal is to be crushed to 3/8 inch x 0 before desliming and cleaning in the heavy medium cyclone, the 1-1/2 inch x 0 raw coal will be fed to the raw coal screen for separating at 3/8 inch. The oversize (from the screen) will be crushed in a Cage-Paktor crusher to 3/8 inch x 0 size which will be recycled to the screen for removing plus 3/8 inch material. The overall 3/8 inch x 0 material will then be deslimed. Three by-passes are provided in the heavy medium cyclone circuits. These are:

1. Primary heavy medium reject can report to the refuse if its ash content is high and no further cleaning in the secondary heavy medium circuit is warranted;
2. The primary heavy reject--crushed to 1/2 mm x 0--normally will be cleaned; however, it can be rejected to the refuse thickener if the ash content is high and no further cleaning is warranted; and
3. The middling product can be loaded out as clean coal if warranted.

All dilute medium slurries collected from drain-and-rise screens used in the heavy medium circuits will be pumped to the Dutch State

Mines magnetite recovery circuit to reclaim the magnetite for reuse. The recovery circuit consists of magnetite classifying cyclones, a magnetic separator, and a magnetite thickener.

The stages of 20-in-diameter cleaning hydrocyclones are furnished to clean 3/8 inch x 0 raw coal to produce clean coal, middlings, and refuse. The maximum top size of raw coal that can be cleaned in a 20-inch-diameter unit is 1 inch. Raw coal and water are pumped to the two primary cleaning hydrocyclones at a concentration of 150 gms per liter. The reject from the primary unit is repulped and pumped to the secondary unit for further cleaning. The 1/2 mm x 0 in the 3/8 inch x 0 size will be cleaned to the degree practical for sulfur removal. The specific gravity of cleaning can be varied by changing the vortex finder length in the cyclone.

The Deister table circuit is fed with raw 3/8 inch x 0 coal through a cyclone classifier. Three products are produced from the Deister table circuit: the clean coal, the middlings, and the refuse. These products will be dewatered in the same three vibrating screens provided for the 20 inch diameter hydrocyclone cleaning circuit. Each product will be automatically sampled in order to establish the performance of each stage of the cleaning unit.

Two stages of 14-inch-diameter cleaning hydrocyclones will be employed to clean 1/2 mm x 100 mesh raw coal down to 250 mesh. The second stage will be used to clean the primary reject and thereby will provide for additional clean coal yield.

The overflow from the combined two-stage 14-inch-diameter hydrocyclone will be pumped to 14-inch-diameter cyclone classifiers for classification at approximately 100 mesh. The plus 100 mesh clean coal will be separated on a two-stage rapped sieve bend after repulping. The underflow (containing the rejected material) will report to the refuse thickener.

The 100 mesh x 0 raw coal from the 14-inch-diameter cyclone classifiers along with the filtrate from the clean coal vacuum filter will report to flotation cells. The flotation cells (35 TPH capacity) are used to reduce ash content of the fine-sized raw coal.

Both Deister tables and 20-inch-diameter cleaning hydrocyclones are to a degree able to clean 1/2 mm x 100 mesh coal. If desirable, the 1/2 mm x 0 fraction from the above cleaning circuits can be pumped to the 14-inch-diameter cyclone classifiers for separating at 100 mesh prior to further processing.

The 1/2 mm x 0 clean coal (includes plus 100 mesh from the rapped sieve bend and minus 100 mesh from the flotation cells) will be dewatered in a disc filter. The filter cake (1/2 mm x 0 material) and plus 1/2 mm clean coal from other cleaning circuits will be combined and conveyed out to the clean coal storage pile prior to shipping.

The flotation tailings and other rejectable 1/2 mm x 0 slurry will be combined and fed to a 90-foot-diameter refuse thickener. The underflow from the refuse thickener will be pumped to a head tank in the

preparation plant for re-use. An emergency pond will be provided for draining the refuse thickener if required.

6.2.2 Roberts and Schaefer Test-Program

The purposes of the test program are:

- To evaluate cleanability of each coal selected for processing (e.g., best cleaning process, yield, refuse, compositions);
- To determine for each selected coal the best cleaning plant configuration from both a technical and economic standpoint;
- To define for each coal tested the cost for one or more levels of cleaning;
- To evaluate the performance of each major piece of equipment used in the plant; and
- To recommend additional experimental work as indicated by the cleaning program.

This effort is composed of three phases: pre-experimental, experimental, and post-experimental. Some elements of the pre-experimental phase will take place during the construction of the plant. Such elements will include the detailed formulation of the experimental program together with implementing arrangements for the purchase, shipment, and receipt of test coals. One coal should be on hand and in plant storage prior to plant start-up and equipment debugging. Two more coals should be on hand before the experimental phase begins. In addition, the pre-experimental phase will include laboratory set-up, the training of plant

and laboratory personnel, and plant start-up with initial equipment adjustments.

The following comments apply to the pre-experimental phase.

1. It is assumed that by the time this phase commences, detailed washability data to be provided by other contractors will be available.
2. A schedule for testing the different coals will be developed. The schedule will be based on coal availabilities with associated washability data.
3. Sampling requirements, on-site laboratory capabilities, and data processing analysis requirements will be characterized so as to aid in planning overall testing sequences.
4. A determination will be made of the best way to process and to analyze the voluminous data that will be generated during the coal testing (experimental) phase of the program.
5. Capital cost data for the various processes that may be used will be collected. These data will be used to define the economics of cleaning particular coals.
6. To insure that all process equipment and instrumentation is optimally maintained, a planned maintenance program will be established.
7. In order to expedite the laboratory work and to operate the laboratory at maximum efficiency, standardized routines for

handling different samples will, insofar as possible, be developed.

8. A written safety program covering plant operations will be developed prior to scheduled plant "start-up". During the plant start-up period, the safety program will be monitored and reviewed as to effectiveness. Revisions will be made as warranted.

9. Arrangements will be made to sell processed clean coal and possible quantities of unprocessed raw coal.

The experimental phase is the major and most important portion of the entire project. This phase will take about 38 months to complete during which 36 coals will be tested in the prototype cleaning plant. Actual testing is estimated to take 36 months, with data processing and evaluation to continue for an additional two months. In general, it is planned that each coal will be tested under enough different conditions to insure that sufficient data will be collected to accomplish test objectives.

In order to insure that each coal (sample) to be tested has acceptable characteristics, each coal test lot will be examined promptly upon delivery to the plant and well in advance of actual testing. Accordingly, the plan is to have each test sample arrive at the plant at least 60 days prior to the start of actual testing. The testing schedule calls for receipt (on the average) of a new coal test sample each month.

For testing a particular coal, the first week of testing will most likely be devoted to insuring the test conditions are proper for a test run. The second week would be devoted to a test run. For many coals, test runs with different test conditions would take place during the third and fourth weeks of a test period.

During the washability studies, samples will be collected at 20 to 25 different locations with an estimated 25 to 30 samples per working-day shift. Samples may vary in size from 30 pounds to perhaps one ton.

In addition to planned sampling, there will be a need for special spot samples. It is estimated that 10 to 15 percent of the efforts of laboratory and sample preparation personnel will be devoted to handling these special samples.

It is anticipated that automatic samplers will be used to collect these samples. Plant personnel will collect, prepare, and perform the required tests on these samples.

For complete characterizations and selected in-process tests of raw coal, clean coal, and refuse, ASTM or other recognized standard methods will be used. Total sulfur in-process testing can be provided using the Leco combustion or equivalent method. For in-process testing purposes, a rapid moisture test is believed acceptable.

For each coal tested, the plant operating data and capital cost data will be carefully documented and evaluated and an individual report will be prepared upon completion of each coal investigated. Each report will include the estimated capital and operating cost associated with

cleaning the investigated coal to one or more sulfur levels. In addition, each report will include supporting and analytical data characterizing the raw coal, clean coal, rejects, and where appropriate, the middlings. It is estimated that data processing, evaluation, and report preparation will require two months per tested coal.

The post-experimental phase will commence upon completion of the final coal washing experiment. The first two months of the post-experimental phase will overlap the last two months of the experimental phase due to the fact that two months will be required to prepare a report covering the final coal tested. The post-experimental phase will consist of two principal activities. These are:

1. Preparation of the final report, and
2. Closing the plant with auxiliary facilities to make ready for subsequent disposal by the Government.

Since an individual report will be prepared for each coal tested, it is visualized that the final report will be an overall summary of the contractual effort. This report will also contain information on coal cleanability based on coal characteristics, coal source area, relative merits of processing various coals, and the performance of different processing techniques as applied to various coals.

At this time, the ultimate disposition of the proposed cleaning plant is not known. It appears prudent that at the end of test program the plant should be put in shape so as to prevent undue deterioration

in absence of usage. Therefore a plant shut-down effort including draining water lines and pumps, disconnecting electric service, applying appropriate lubricants and protective coatings, inventorying assets, and providing physical security measures should be applied to the deactivated plant. It is estimated that four months will be required to complete the post-experimental phase of this effort.

6.2.3 Roberts and Schaefer Capital and Operating Costs

Capital and operating cost estimates based on the design study cover the prototype cleaning plant and are predicated on the following:

- The plant contains a fully equipped testing laboratory;
- The plant contains an analytical laboratory;
- Suitable office facilities are contained in the plant;
- Operating costs are based on a pre-experimental period of 12 months, an experimental period of 38 months, and a post-experimental period of 4 months, there being a two month overlap of the experimental and post-experimental phases; and
- Test lots of 10,000 tons.

The estimated program cost is $16,457,965. Cost details are provided in Table XXI. The above total does not include estimated credits received from the sale of processed coal and credits from disposal of plant equipment after program completion. Total credits are estimated to amount to $2,000,000.

The initial Roberts and Schaefer overall program of work was reviewed to determine how the overall program might be modified to reduce

TABLE XXI

COST ESTIMATES FOR FIFTY-TWO MONTH PROGRAM

A.	Plant Cost		
	Design	$ 175,000	
	Equipment (machinery only)	1,500,000	
	Construction (including building)	1,525,000	
	Test facilities for process evaluation and quality control	698,000	
			$3,898,000
B.	Operating Costs		
	Direct labor	998,210	
	Travel, relocating, report reproduction, computer use fees	214,700	
	Overhead and personnel services	569,205	
	Utilities	323,000	
	Test Coals	3,600,000	
	Expendable supplies	724,920	
	Plant and equipment maintenance	600,000	
	General administration (e.g., postage, telephone, office equipment)	1,169,962	
			8,199,997
C.	Laboratory services (via contract)		
	Preliminary engineering	20,000	
	Laboratory work	3,353,200	
	Personnel service (1st year only)	56,400	
			3,429,600
D.	Fee (8% of B and C)		930,368
	Total		$16,457,965

overall cost without unduly sacrificing program objectives. As a result of this effort, an alternative program to be accomplished in less time and at lower cost was defined. For the alternate lower cost program, the overall program of work including the detailed design and construction of the prototype plant, development of the detailed experimental program and in-plant testing of 36 coals is estimated to require 44 months. The alternative lower priced program is based on the following:

- The amount of each of the 36 coals to be tested in the prototype plant will be 4,000 rather than the initially recommended 10,000 tons;
- The experimental work is programmed for 24 months (rather than 36 months);
- The overall effort of work covering the design and construction of the prototype coal cleaning plant and the execution of the experimental work has been programmed for 44 months (rather than 52 months); and
- The amount of on-site laboratory work and, consequently, the equipment and personnel need have been reduced.

Based on these changes, the cost for the modified program concept was estimated at $8,923,200; details are provided in Table XXII. The modified program cost estimate does not include credits received from the sale of processed coal and credits from the disposal of plant equipment after program completion. These credits are estimated to amount to $1,000,000.

TABLE XXII

COST ESTIMATES FOR FORTY-FOUR MONTH PROGRAM

A. Plant Cost		
Design	$ 175,000	
Equipment (machinery only)	1,500,000	
Construction (including building)	1,410,000	
Test facilities for process evaluation and quality control	323,500	
		$3,408,500
B. Operating Costs		
Direct labor	1,415,690	
Travel, relocating, report reproduction computer use fees	179,700	
Overhead and personnel services	788,550	
Test coals	1,440,000	
Expendable supplies	316,900	
Utilities	201,300	
Plant equipment maintenance	400,000	
Contract testing	30,000	
General administrative	334,055	
Fee	408,505	
		$5,514,700
Total		$8,923,200

6.3 Design of the McNally Pittsburg Prototype Cleaning Plant, Test Plan, and Costs[21]

6.3.1 McNally Pittsburg Plant Design

The design of the prototype plant required special considerations to ensure that it will suitably process a wide variety of coals from which satisfactory clean coals with acceptable sulfur content could be produced. The plant design provides for flexibility through alternate circuits and equipment choices which can be run in any combination to permit the handling of coals of different sizes and widely varying washability characteristics. The recovery and concentration of pyrite for possible future commercial utilization were also considered. In the absence of established standard methods for the recovery of pyrite from the washery refuse, alternate circuits as well as alternate equipment items were deemed necessary to enable the determination of the most suitable recovery processes. All of these considerations were taken into account in arriving at the prototype plant design concept.

The recommended plant has a 50 TPH capacity, and contains a coarse coal circuit with a heavy media cyclone for cleaning the various sizes of 1-1/2 inch x 3/8 inch, 1-1/2 inch x 14 mesh, 3/4 inch x 3/8 inch, 3/4 inch x 14 mesh, and 3/8 inch x 14 mesh coals, and a fine coal circuit for treating fractions 3/8 inch and less. Coals which would be crushed to 3/8 inch x 0 or 14 mesh x 0 would be washed in the fine coal circuits which has available primary and secondary McNally-Visman Tri-

cone. The secondary Visman Tricone (unlike the primary Tricone) can be used to treat high specific gravity material at a high cut point.

Besides the fine and coarse coal circuits, adequate arrangements have been made for unloading, handling, and crushing the raw coal as well as handling of clean coal and disposal of refuse. A water clarification system is included to provide for cleaning and subsequent reuse of water, thereby substantially reducing the amount of water required by the plant. An 8000-ton-capacity raw coal storage facility has been provided through two 4000-ton silos for storing raw coal sufficient for one month's operation.

In essence, the recommended prototype plant has been provided with alternate circuits and equipment choices which can be run in any combination so that it will be able to handle coals of different sizes and widely varying washability characteristics. In the absence of standard methods for the recovery of pyrite from the washery refuse, alternate circuits as well as alternate equipment are provided to determine the most suitable process for pyrite recovery from any given coal.

Although not included in the provided plant design, the installation of a fluid bed type thermal dryer was recommended for consideration. The dryer could be used to treat fine coals with high moisture content and would provide for obtaining valuable operating information. The collected data could be used to assist coal cleaning plant and dust collector designers and plant operators to meet air pollution restrictions in the supply and operation of full scale plants and equipment.

Specifics concerning the cleaning plant and processes are as follows:

The cleaning process starts with raw coal crushed in a rotary breaker and stored in one of two 4000-ton steel silos. The two silos provide the storage capacity necessary for running the plant for 22 days at one shift per day with an average feed rate of 50 TPH.

Although the overall plant was designed for an average capacity of 50 TPH, the raw coal crusher with associated conveyor belts, screens, etc., was designed with excess capacity so as to permit an increase in load in the heavy media cyclone. The raw coal scalping unit has interchangeable screens for 14 mesh or 3/8 inch. The 14 mesh x 0 or 3/8 inch x 0 size coal from the scalping screen will normally be conveyed to 8-inch primary McNally Visman Tricones for washing.

A crusher, provided after the heavy media cyclone sink screen, will crush the refuse to liberate interlocked pyrite particles prior to further washing in McNally Visman Tricones. Crushed refuse from the heavy media cyclone or the coal from the raw coal scalping screen will be processed in eight 8-inch primary Visman Tricones in order to recover low sulfur coal.

High sulfur refuse from the primary McNally Visman Tricones can be washed in 8-inch secondary McNally Visman Tricones or in sequence through secondary McNally Visman Tricones and the Deister coal tables. The coal table was specified to provide the means to determine the feasibility as well as efficiency of recoverying low sulfur coal from pyrite rich refuse by employing a tricone and/or a coal table. Refuse

from the secondary McNally Visman Tricones can also be fed to two ore tables to treat the heavier pyrite/refuse fraction.

Tailings from the magnetite separator and the minus 1/2 mm fraction from the classifying cyclone underflow can be processed in the flotation cells to recover low sulfur coal. When recovery is not required, the flotation cells can be by-passed and the tailings pumped to the waste pond.

The flotation concentrate, or coal, if found low in sulfur, will be filtered and mixed with the coarse washed coal and conveyed to loading. If the coal concentrate from the flotation cell is found high in sulfur and not worthy of recovery, it will be diverted to the waste pond.

Proper reagents to selectively float coal and depress pyrite along with other gangue materials present in the coal slurry feed to the flotation cell have not yet been developed for all the different coals. Work is continuing in this field and the prototype plant will provide an excellent test facility to carry out tests with the various types of coals selected for processing. Hopefully, it may be possible in the operation of this plant to find a suitable collector for the selective flotation of coal.

Adequate arrangements for the recovery of the magnetite from the dilute medium have been provided. The dilute medium will be thickened in a thickener and the magnetite recovered by a double drum magnetite separator for system reuse. As the washed coal is expected to have high surface moisture, the recommendation was made that consideration

be given to the installation of a fluid bed type thermal dryer for drying the fine coal. Installation of such a dryer will enable the collection of valuable information on:

- Dryer fuel consumption versus dust loss as a function of operating conditions,
- Size distributions of solids and dust fraction within the processing system and those escaping to the atmosphere, and
- Selection of dust collecting equipment required to meet the dust emission code of the various states.

6.3.2 McNally Pittsburg Test-Program

The purposes of the testing program are:

- To evaluate performances of each major piece of equipment used in the plant;
- To evaluate each coal selected for processing;
- To define the proper circuit for a given coal;
- To evaluate overall performance of the plant for cost analysis; and
- To make comprehensive plant studies including material balances, ash, total sulfur, and pyritic sulfur content for each coal.

Approximately 8000 tons of coal will be required (i.e., delivered to the plant) for each coal tested. For each test, a raw coal sample (1-1/2 inch x 0) will be collected one to two weeks prior to test initiation. This sample will be collected by an automatic sampler and will be based on sampling lots of 2800 tons in seven hours at a 400 TPH feed.

The sampler will take nine cuts per hour at 55.6 pounds per cut for a total sample of 500 pounds per hour. Samples will be sent to two bins, set to receive alternate cuts, for a total of 250 pounds per hour for each bin. This procedure will satisfy all conditions for ASTM D2234-65T on mechanical sampling of coal and D492048 on sampling coals classified according to ash content. It will also provide the proper gross sample with which to make the washability study from which plant settings will be determined.

The primary gross sample will be screened to produce the following sizes:

1-1/2 inch x 3/5 inch

3/4 inch x 3/8 inch

3/8 inch x 14 mesh

14 mesh x 28 mesh

28 mesh x 48 mesh

48 mesh x 0.

Float and sink separations will be run on each size fraction at the following specific gravities: 1.30, 1.35, 1.40, 1.50, 1.60, 1.90, 2.20, 2.50, and 2.80. The refuse will be visually examined to see if heavier gravities are required. Laboratory tests will be performed to define dry ash, total sulfur, and pyritic sulfur contents of each size gravity fraction. Related coal compositions will be calculated for each coal

size which might be used as feed to a piece of equipment in the cleaning plant. These coal sizes are:

1-1/2 inch x 3/8 inch

3/8 inch x 14 mesh

1-1/2 inch x 14 mesh

3/8 inch x 0

14 mesh x 0.

Based on the data, operating personnel will anticipate an optimum setting for each piece of equipment. As a new coal is first fed to the plant, samples will be collected to check the specific gravity of operation. When the various circuits are set to the operators' satisfaction, daily runs can be started to determine optimum plant conditions to provide for the maximum sulfur removal. In some cases it is likely that it will be necessary to check more than one set of alternative conditions to determine the point of optimum sulfur reduction. After the equipment and the circuits are set for their best performance in sulfur reduction, prolonged test runs will be made with all the sampling stations of all the circuits in use so that a complete plant evaluation can be made for each coal washed. The total plant is specified to contain 29 sampling points (i.e., 27 automatic plus 2 manual).

The plant feed and final products for each coal will be analyzed to determine compositions and the burning and slagging characteristics of the feed as well as the final products. Regular checks will also be

made on the plant effluent as well as on any pond water or streams which might be affected by the plant operation.

Cleaning and equipment performance data generated in pursuance of this effort should be properly cataloged and stored for ready access. With this in view, microfilming arrangements together with an adequate storage and retrieval system have been suggested. Closed circuit TV communication is also specified for confidential transmission of data to the plant and laboratory operations.

The testing program design intent is to permit comprehensive coverage of all sampling stations or only a few stations as may be dictated by coals and circuits being tested. Sufficient personnel and equipment are specified to permit completion of all necessary tests on a day's run prior to the start of the next day's run. In addition to the daily tests, a washability test is required prior to each program for each coal. At the end of each month, one or more comprehensive plant studies including material balances and ash, sulfur, and pyritic sulfur balances are specified. This work will require substantial personnel and many auxiliary tasks will have to be performed at off hours so as to not interfere with the routine tests.

The laboratory staff, in addition to maintaining the plant testing program, will regularly collect samples of makeup and effluent water for analyses. Therefore, all water coming onto the property and leaving the property will be checked.

6.3.3 McNally Pittsburg Capital and Operating Costs

Capital and operating cost estimates are based on the prototype cleaning plant plus the following:

- The plant contains a fully equipped testing laboratory,
- The plant contains an analytical laboratory,
- Suitable office facilities are contained in the plant,
- One year is required for total plant installation time,
- Plant start up time is six months, and
- Plant operating time is three years.

Estimated costs are:

	LABORATORY OFFICE	PLANT	TOTAL
Estimated capital investment for equipment & installation	$1,078,191	$2,158,000	$3,236,191
Six month start-up costs	911,514	253,335	1,164,849
Operating costs for 3 years	5,430,000	1,520,010	6,950,010
Insurance for 4-1/2 years	11,540	44,185	55,725
Totals	$7,431,245	$3,975,530	$11,406,775

Depreciated value of the plant and laboratory equipment at the end of 4-1/2 years has been assumed to be 10 percent of the capital investment or $323,619. The cost of 96,000 tons of raw coal (for washing at half the rated capacity during start-up and at 50 TPH for three years) was estimated to be $3,276,000. The sale price of the washed coal was estimated to be $995,163.

6.4 Data Evaluation[22]

The Roberts and Schaefer Company prototype plant design study was judged the most appropriate in addressing the overall EPA program goal. As a result, Roberts and Schaefer was given the responsibility to develop a detailed test program for the prototype coal cleaning plant. The resulting program contained inputs from Roberts and Schaefer and the McNally Pittsburg prototype plant design studies, the Bureau of Mines coal preparation group, EPA technical personnel, and from Commercial Testing and Engineering, Incorporated.

A basic goal of the EPA coal cleaning program is to develop a correlation of the cleanability of any coal with its raw coal physical properties. This would involve the identification and quantification of those physical coal properties which correlate with cleanability including the identification of the most appropriate process, process parameters (e.g., coal size, specific gravity of separation), product yield, and the sulfur and ash characteristics of the clean coal product.

In general, the cleaning capabilities of operating preparation plants are ascertained by sampling, analyses, and calculations. The same applies to the performance testing of an experimental prototype coal cleaning plant.

Since the calculations involved in predicting cleaning results and in evaluating the test results are time-consuming, a computer is specified to perform the required calculations. The design of the prototype test program is based on the use of computer processing to provide for

timely and economical reduction of a voluminous amount of data and to rapidly predict plant settings for subsequent runs on a given coal. This quick response would be mandatory for completely evaluating a given coal in a one-week test period.

Four computer programs are available[3] and will be used to ultimately provide one program which will be used for predicting the attainable sulfur and ash levels at selected yields from a given coal. The final computer program will basically evolve from a continuing examination and modification of an existing "Predicting Program." The basic "Predicting Program" and its modifications will be used to define the plant flow scheme which best fits the cleaning objectives. The other three referenced computer programs will aid in evaluating the validity and accuracy of the prediction program and its successors.

The four presently available programs are:

Program No. 1 - The Predicting Program:

The program for predicting the cleaning results of a plant or for predicting the results of a piece of cleaning equipment in a plant using (1) performance data that is already known from experience on the various pieces of cleaning equipment, and (2) the grainsize distribution and washabilities of the raw coal determined by suitable laboratory test work;

Program No. 2 - The Distribution Program:

The program for establishing the distribution-curve data of cleaning equipment from data acquired as a result of prototype plant operations.

Program No. 3 - The Classification Program:

The program for establishing the classification curve of classifying equipment from data acquired as a result of prototype plant operations.

Program No. 4 - The Solids Balance Program:

The program for balancing the solids flow (tons) or the solids flow rate (tons per hour) with the ash, pyritic sulfur, and total sulfur content of the solids through each line of the flow scheme.

The programs will permit the calculations required to characterize the sharpness and efficiency of a separation in any cleaning unit in the plant. As data become increasingly available, a running analysis of variance will delineate the sensitive variations in operating conditions or physical characteristics of the coals which affect cleaning performance. Factors to compensate for these variations will then be defined and incorporated in the computer program. Even though the initial programs do not cover sulfur content of the coal, inclusion of this parameter in the program will provide the ability to project the sulfur and ash contents in the clean coal based on raw coal characteristics.

It is anticipated that the final program will include raw coal data obtained from the following:

(1) Sample crushed to three top sizes with screen analyses for each with ash and sulfur determination for each size fraction.

(2) Washability relationships derived from float-sink tests for each of the three size samples and the ash and sulfur analyses for each specific gravity fraction.

(3) Hardgrove grindability index, BTU, and ultimate and proximate analyses of each coal sample.

6.4.1 Details of Presently Available Computer Programs

The following presents information on each of the four presently available computer programs.

a) Program No. 1 - The Predicting Program:

The inputs for the predicting program are the percent by weight and the ash content for each specific gravity fraction (i.e., from the washability), and an ashline relationship (between specific gravity and percent ash) of the raw coal. The computer will interpolate and extrapolate the washability, calculate the yield, the specific gravity composition, and the ash content of the end products for a separation by employing distribution-curve data of the desired cleaning equipment. The calculation will be based either on a given specific gravity of separation or a required ash content for the clean coal.

Three systems of separation are available. The first is a separation arrangement in which clean coal and refuse are separated and then a middling product is separated from the clean coal. The second is a reverse of this, the middling product being separated from the refuse.

The third arrangement involves middlings being separated from both clean coal and refuse after these two have been separated from each other.

The program takes the washability data associated with each size fraction of the raw coal in the order provided by the data card set until all size fractions are processed. If more than one separation is to be performed on any size fraction of the coal, the cleaning equipment for each separation will be specified. The results of the program cleaning calculations become data supplied to the program for calculation of the results of the next separation in the system.

b) Program No. 2 - The Distribution Curve Program

This program will be used to establish washing equipment distribution-curve data based on results obtained from the prototype plant tests. For the program, the input is the percent by weight from each specific gravity fraction in each grain-size range of the feed and end products. In the case of a cleaning unit making only one separation, three parameters are involved: feed, clean coal, and refuse. In the case of two separations, four parameters are involved: feed, clean coal, middlings, and refuse.

With this input the computer proceeds to calculate the percent yield for clean coal, for middlings in the case of a two-separation process, and for refuse. Employing the yield calculation result, a reconstructed feed is determined and the distribution numbers calculated for each piece of equipment. The reconstructed (or reconstituted) feed, as opposed to the actual sampled feed, is used as a check on the accuracy

of both the analytical and the sampling procedures. The reconstructed feed is determined by adding the end products together on a weighted basis for each size and specific gravity composition, based on the calculated yield percentages.

c) Program No. 3 - The Classification Program

Program No. 3 is for establishing the classification curve data of classifying cyclones and sieve bends from data obtained from prototype plant testing.

With the help of classification curves obtained by testing, the standard classification curve already known from experience for classifying cyclones and the classification curve known for sieve bends can be checked and, if necessary, modified. Using the standard classification curve, the grainsize composition of the end products of the classification equipment can be predicted for different grainsize compositions of the feed.

A classifying cyclone or a sieve bend component only is not always used for classifying a product (water plus solids). A combination of such components can also be employed. The program is written in such a way that not only the test results of a single component but also the test results of a combination can be used as input. In such a case the computer calculates the classification-curve data for both pieces of equipment with less sampling and analytical test work than would be the case if both units were treated separately.

d) Program No. 4 - The Solids Balance Program

This program is to be used for balancing the solids flow (tons), or the solids flow rate (tons per hour), with its ash, pyritic sulfur, and total sulfur content through each line of the flow scheme. The balancing provides projections on the overall reduction of ash, pyritic sulfur, and total sulfur in the clean coal obtainable on a full plant basis, and the ash and sulfur reduction attributable to each piece of cleaning, sizing, and classifying equipment.

The computer program will allow the simulation of five major and thirty-three minor flow schemes. By making use of balancing techniques, the program usage will reduce the requirements for sampling and analytical test work.

6.4.2 Correlation of Coal Characteristics with Cleaning Results (Multiple Regression Analysis)

A continual analysis of the variations in the operating conditions of the plant and in the physical characteristics of the coal that affect cleaning equipment performance will be provided. Data on the performance of each piece of cleaning equipment will be continuously collected, through sampling and analysis, and the raw coals processed will be analyzed with respect to certain major properties. The examined properties include grindability, pyritic sulfur content, and the electrokinetic potential. The equipment parameters which will be varied include the size fraction of coal being cleaned and the tons per hour processed. In the analysis of variations an attempt will be made to establish whether a correlation can be made between pairs of observations or groups of ob-

servations. The pairs of observations will be in the form of scattered data in which an attempt will be made to find functional relationships. These relationships may be linear or non-linear. If they are linear, a line of regression will be determined taking each variable in turn as the independent variable by the method of least squares, as used in a linear regression analysis. If they are non-linear, an attempt will be made to determine what sort of function is represented. For instance, two variables may be parabolically or quadratically related and perhaps an equation describing the relationship can be determined. In the case of a correlation attempt on groups of observations, multiple correlations will be attempted by a multiple regression analysis.

The purposes of the analysis of variations are to determine which coal properties and/or operating conditions prove to be significant parameters and to determine, if possible, the relationship between these parameters. Once this is known to any substantial degree, predictions of greater confidence may be provided.

7.0 PYRITE UTILIZATION ECONOMIC STUDY

7.1 Purposes of the Study; Overview and Approach

Commercial coal cleaning plants are designed to remove non-carbonaceous materials from the coal. The composition of the reject material varies with the type and source of the coal. It consists principally of shale, sandstone, clayey substances, and pyrites (iron-sulfur compounds) along with carbonaceous materials unavoidably lost.

Several of the reject constituents have commercial value, but the low concentration of these materials and their relatively low market price have in the past rendered their recovery and sale commercially unattractive. One apparent exception is pyritic and carbonaceous material, which can serve as a source of sulfur, sulfur compounds, and energy. Concentrations of pyrites in the reject from cleaning certain coals appear sufficient to make recovery of sulfur values economically feasible. This would be more likely if the sulfur recovery can be combined with combustion processes so that the energy from the combustion of pyrites, as well as the coal fraction remaining in the rejects, can be utilized.

The purposes of the Pyrite Utilization Economic Study portion of EPA's overall pyrite coal program are:

(1) To investigate the economics of utilizing the pyrites obtained from coal beneficiation by determining (a) the degree to which it is possible to offset the increased costs involved in maximizing the reduction of sulfur content and (b) the ability to recover economic values in reject material;

(2) To evaluate the applicability of alternative commercial processes for recovering energy and chemical values from coal cleaning reject material; and

(3) To design, construct, and operate a plant that would demonstrate the technical and economic feasibility of the processes.

Investigations concerned with the first two purposes listed above were conducted concurrently. In 1967, EPA awarded a contract to the Bechtel Corporation, assisted by Stanford Research Institute, to perform a general review and evaluation of the technology and costs of available commercial processes for utilizing pyrite-coal, and to investigate the technical and economic feasibility of certain processes in greater detail. Also in 1967, EPA awarded a contract to Arthur D. Little, Inc., assisted by Dorr-Oliver, Inc., to determine the costs and benefits of processing pyrites removed from coal. The A. D. Little study concentrated on the technology and economics of fluidized bed roasting of pyrite-coal, followed by conversion of sulfur dioxide to sulfuric acid by the contact process. A principal goal of the latter study was to evaluate the acceptability of such processes to the industries involved (coal, chemical, utilities, steel, etc.). The results of these two studies of various recovery processes and the market potential for recovered products and by-products are presented in the remaining portions of Section 7.

The Bechtel and A. D. Little studies lead to the general conclusion that existing technology can readily be adapted to recovery of

sufficient quantities of energy and sulfur values from the reject material from coal cleaning operation to be of commercial interest. However, the economics of such recovery operations are marginal, and the economic viability of these operations is closely related to the supply and selling price of elemental sulfur.

On the basis of technical and economic data developed in these two studies, EPA decided to look more closely at a system for burning the high-sulfur, high-ash reject materials produced by coal desulfurization. This decision was based on the applicability of proven technology and on economic analyses of various processing systems. A contract was subsequently awarded (in 1969) to Chemical Construction Company (Chemico) to (1) select the most appropriate sulfur recovery process and design a high-sulfur combustor system, (2) investigate combustion characteristics of high-sulfur fuels, and (3) prepare a conceptual design and cost estimate of a prototype plant employing the high sulfur combustor. Chemico was assisted by the Foster Wheeler Corporation in this undertaking. Results of the design and analysis effort are presented in Section 8 of this report.

7.2 Description of Candidate Recovery Processes

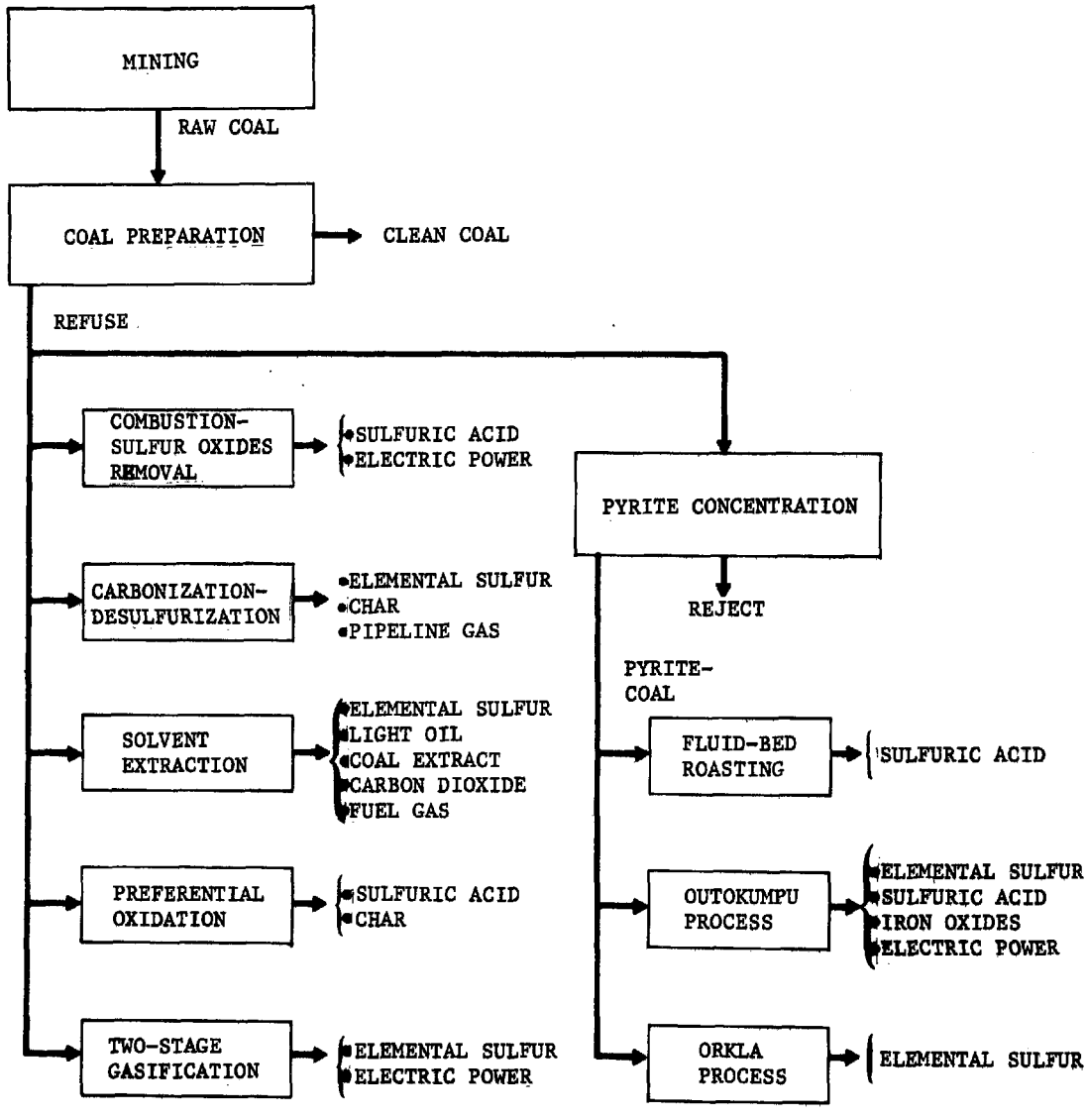
Chemical and energy values can be recovered from pyrite-coal by a number of processes. These employ markedly different approaches and yield different combinations of products. Certain processes accept the entire stream of reject material from a coal preparation plant while others require additional concentration of the pyrite.

Eight separate processes were selected for evaluation by Bechtel Corp. Three of the eight (Fluid Bed, Outokumpu, and Orkla) were identified as being commercially available for the processing of pyrites for metallurgical purposes, but all three have technical and economic limitations for utilization of the total refuse streams from coal cleaning operations. Thus, evaluations were made of five processes that had not reached commercial application. These five additional processes accept the total refuse stream from a conventional coal preparation plant, while the presently available commercial processes require additional pyrite concentration. All of the processes considered and their principal products are identified in Figure 25 with descriptions following. The marketing of product sulfur and sulfuric acid is discussed in Section 7.3, but it should be mentioned at this point that recovery of sulfur values in the form of elemental sulfur is sometimes preferable to recovery in the form of sulfuric acid because of the high shipping costs for the acid. This consideration does not apply when there is a market for sulfuric acid near the reject processing plant.

7.2.1 Brief Description of Recovery Processes

The eight recovery processes evaluated are described briefly in the following paragraphs.* These descriptions include comments on the applicability of each for processing pyrite-coal. It should be noted that none of those processes that accept the entire refuse stream was in com-

*More complete descriptions including process flow diagrams are given in Reference 23.



SOURCE: REFERENCE 23 (1968)

FIGURE 25
REFUSE PROCESSES

mercial operation at the time this study was conducted. Processes that accept a concentrated pyrite feed were in commercial use, but were utilizing mined pyrites, not pyrite-coal reject materials.

Combustion/Sulfur-Oxides-Removal

The reject material is burned in a combustor designed for high-sulfur, high-ash feed. Heat from the combustion is used to generate steam which is used in turn to generate electric power. Sulfur oxides produced in the combustion are recovered from the combustion gas and used to form sulfuric acid. Several processes have been proposed for sulfur dioxide recovery; the Monsanto Catalytic Oxidation process was selected as a basis for costing and evaluating the overall process. In the Cat-Ox process, sulfur dioxide in the combustion gas stream is oxidized in contact with a catalyst to form sulfur trioxide, which is absorbed in water to form marketable sulfuric acid.

Although the Cat-Ox process was not in commercial use at the time of this study, it had been tested in a large-scale pilot plant.

Carbonization-Desulfurization

This approach to material and energy value recovery involves a relatively complex set of reactions in which coal and pyrites in the reject stream are decomposed by heat. Sulfur is removed from the decomposition products to form elemental sulfur; a high-BTU, low-sulfur combustible gas; low-sulfur char; and other solid products.

The carbonization-desulfurization approach can be illustrated by a highly abbreviated (and incomplete) description of a specific process.* Volatile components are removed from coal in the reject material by contact with a very hot char (produced by another step in the process). Volatilized components are de-acidified by amine stripping, then passed through a methanator where constituent carbon monoxide and hydrogen react to form methane, which is then compressed to form a pipeline gas. The solid components of the feed stream are desulfurized by reaction with hydrogen to form hydrogen sulfide and a low-sulfur solid char. Sulfur is removed from the hydrogen sulfide by reaction with dolomite to form a

*The Consolidated Coal Company CO_2 Acceptor Process.

solid sulfide, which is oxidized to remove sulfur as sulfur dioxide and to regenerate the dolomite for reuse. The sulfur dioxide is reduced by reaction with hydrogen sulfide or carbon monoxide (from other process steps) to form elemental sulfur, water, and carbon dioxide. The useful products are high-BTU, low-sulfur pipeline gas; low-sulfur char; and sulfur.

This technically complex process would be further complicated by the use of pyrite-coal instead of run-of-mine coal. The effects of additional ash on the process and on the value of the char are not well understood. The process requires high capital investment. Preliminary economic studies are not encouraging.

Solvent Extraction*

In this process, the coal in the refuse stream is dissolved in a solvent. A low sulfur, low ash solid coal extract is recovered from the solvent. Depending on the specific processes used, other products may include light oil, fuel gas, and sulfur.

This process is characterized by its technical complexity and requirements for high capital investment. It is still under development, using run-of-mine coal. The effects of using pyrite-coal rejects for the feed material are not well known. Prospects for processing coal-pyrite rejects, based on preliminary economic analysis and current developmental status, are not attractive but may become so through continued research and development.

Preferential Oxidation

The reject stream is allowed to react with a limited quantity of oxygen at a temperature range that promotes oxidation of pyritic sulfur in preference to carbon. This temperature (around 800°F) must be carefully controlled to prevent excessive volatilization and oxidation of the coal. Temperature control is a major technical problem. The sulfur dioxide formed by oxidation of pyrite is converted to sulfuric acid.

The process has been studied on a laboratory scale. Data are not adequate for useful economic analysis.

*It should be recognized that the process termed "solvent extraction" here (and in Reference 23) involves dissolution of the carbonaceous components of coal, not the ash or pyritic components, and in this respect is similar to the Pittsburg-Midway "Solvent Refined Coal" process.

Two Stage Gasification Process

A gasifier, fired with coal refuse, operates in a system that converts the fuel value to electricity and recovers elemental sulfur from the gas. Hot gases which contain most of the sulfur as H_2S leave the top of the gasification furnace, generate steam in a heat recovery boiler, then preheat air for combustion of these gases later in the system. Gas, now at 250°F, is scrubbed with 100°F water to remove dust and condense water vapor. Hydrogen sulfide is removed from the gas by an absorbent solution and then converted to elemental sulfur by a Claus kiln or perhaps the Giammarco-Vetrocoke process. Clean gas from this system would contain about 1.0 grain of hydrogen sulfide per cubic foot, and sulfur recovery would be about 98 percent of that absorbed. The sulfur would probably be contaminated with small amounts of arsenic from the absorbent solution but purification with limewater would be practical. The clean gas from the sulfur recovery steps would be burned with the preheated air from the heat exchange in a boiler equipped for preheating combustion air for the gasifier. Waste gas at about 450°F would pass to a stack. Steam from this boiler and from the heat recovery boiler would be available for electrical power generation.

Fluid-Bed Pyrite Roasting

Crushed pyrite (about 1/4 inch top size), on a grate or bed through which an upflow of air keeps the material turbulent, is oxidized at high temperature to produce sulfur dioxide and iron oxide (principally hematite). The sulfur dioxide in the gas stream is oxidized catalytically to produce concentrated sulfuric acid. The solid residue can be further processed to produce a material similar to a high grade iron ore. Since the oxidation of pyrite under these conditions is self sustaining and exothermic, the heat produced can be used to generate steam which then can be used to generate electric power. The products of this process are a marketable grade of sulfuric acid (93 to 98 percent H_2SO_4), electric power (or steam), and a solid calcine material. Iron from the pyrite may remain in the calcine as hematite (Fe_2O_3), or it may be removed as a separate product, usually in the form of magnetite (Fe_3O_4) suitable for steelmaking.

This process is widely used on a commercial scale for sulfuric acid manufacture from mined pyrites. In at least one installation it also produces iron oxide pellets for steelmaking. The process usually requires pyrite containing 40 to 50 percent sulfur. Since the pyrite-coal reject stream from a coal preparation plant typically

contains 4 to 25 percent sulfur, a pyrite concentration step is required.

Preliminary economic analysis shows this process to be one of the more promising for recovering energy and sulfur values from coal-pyrite rejects.

Outokumpu Process

In this process, pyrites are flash smelted upon contact with hot gases from an oil burner. Labile sulfur in the pyrites volatilizes in the form of elemental sulfur vapor, sulfur dioxide, and hydrogen sulfide. The sulfur vapor is condensed and sulfur is recovered from the sulfur dioxide and hydrogen sulfide in the form of elemental sulfur.

Fixed sulfur in the pyrites remains as ferrous sulfide matte. This is roasted to produce iron-bearing calcine, from which iron can be recovered, and sulfur dioxide, which is converted to sulfuric acid. Heat produced at the smelting step and ferrous sulfide roasting step of this process can be used to generate steam and electric power.

This process is in commercial operation in Finland. It appears suited to a set of conditions existing there, where there is a market for all of its principal products--sulfur, acid, iron oxide, and electric power. The economics of the process are not attractive for use in the U.S., where different market conditions exist for its products, particularly for iron oxide. If a pyrite-coal feed is used, yields would be lower and the economic prospects even less attractive.

Orkla Process

This process is used in Norway to recover sulfur and metallic values from copper-bearing pyrites. It employs a furnace, similar to a blast furnace, which is charged with lump pyrites, coke, sand, and limestone. Labile sulfur in the pyrites volatilizes initially without oxidation as elemental sulfur in the upper part of the furnace where no oxygen is present. Fixed sulfur remains as metallic sulfides, which sink to the smelting zone of the furnace, where a portion oxidizes to form sulfur dioxide and iron oxide, while the remainder forms a matte of cupreous sulfide and iron sulfide, which is resmelted to obtain copper. The iron oxide reacts with silica and limestone to form a slag, while a portion of the sulfur dioxide is reduced by coke to form elemental sulfur. The remaining sulfur dioxide is reacted catalytically with gaseous sulfur compounds formed at various processing steps to form elemental sulfur and

by-product gases. Principal products are copper and elemental sulfur, with a by-product slag of high iron content.

While the Orkla process is the only one of the eight evaluated processes operating on a commercial scale that recovers most of the pyritic sulfur in elemental form, it has certain inherent disadvantages. It requires that the pyrite feed be in lump form, which would necessitate briquetting of pyrite coal produced by a coal preparation plant. Process economics, which are somewhat marginal using a cupriferous pyrite feed, are heavily dependent on recovery of copper, which, of course, would not be feasible from most pyrite coal feeds. Although the process appears well suited to the situation in Norway, it does not appear economically attractive or readily adaptable technically to the processing of pyrite coal in the U.S.

The eight processes described above are summarized in Table XXIII. This table indicates the advantages, limitations, and economic characteristics of each process, in addition to identifying the type of feedstock, principal products, and major processing steps.

7.2.2 Preliminary Economic Studies of Selected Processes

To obtain a comparison of the economics of the above processes, five were analyzed in a given scenario using a consistent set of assumptions relative to size of operation, logistics, power and labor costs, product market prices, etc. The following processes were subjected to this type of analysis:

- Refuse Combustion/Sulfur-Oxides-Removal;
- Fluid Bed Roasting;
- Outokumpu;
- Carbonization-Desulfurization;
- Solvent Extraction.

All of the above are either in commercial operation or reached the pilot plant stage of development. The remaining three processes were not

TABLE XXIII

SUMMARY OF PROCESSES FOR UTILIZING COAL REFUSE

PROCESS	FEED	PRODUCTS	PROCESS DESCRIPTION	ADVANTAGES	LIMITATIONS	ECONOMICS
Combustion-Sulfur Oxides Removal	Entire refuse stream	Sulfuric Acid (78%) Electricity	Coal refuse is burned in a stream generator designed for high ash and sulfur fuel. Sulfur is oxidized to sulfur dioxide which is catalytically converted to SO_3 followed by recovery of sulfuric acid. Process is in developmental status	Does not require pyrite concentration Based on relatively simple, well-known technical principles Products are usually marketable	Sulfuric acid product is slightly discolored and limited to about 78 percent concentration Market radius is limited by shipping cost of acid (usually about 200 miles maximum) Final solution is required to select economical corrosion resistant materials of construction. Pilot plant status	Most promising process
Carbonization-Desulfurization	Entire refuse stream	Sulfur Pipeline gas Char	Coal refuse is dried, devolatized, then desulfurized in a fluid bed with gas containing about 50% H_2. Sulfur forms H_2S which is removed by a dolomite acceptor. Dolomite is regenerated. H_2S is converted to elemental sulfur, process gas is converted to fuel gas by a methanation reaction.	Requires no pyrite concentration; uses entire refuse stream Recovers sulfur in elemental form	Complex, multioperation process with many technical problems to solve High-ash char may not be marketable; this product may retain sulfur Pilot plant status	High capital and net operating costs
Solvent Extraction	Entire refuse stream	Sulfur Light oil Coal extract Carbon dioxide Fuel gas	Coal fraction of the refuse is dissolved in solvent derived from the coal itself in the presence of hydrogen. Solution is filtered to remove ash. Filtrate is evaporated to recover solvent, and liquid coal extract is solidified. The solvent is distilled to yield light oil; the heavier fraction is recycled. Process gas containing H_2S, removed along with solvent vapor, is passed through an amine treatment to remove the acid gas. Acid gas is processed to recover elemental sulfur. Process gas is steam reformed to give H_2S for recycle and CO_2 byproduct.	Requires no pyrite concentration; uses entire refuse stream Produces high quality products	Complex process; it requires further development and solution of technical problems Economics favor very large-scale operation Pilot plant status	Highest capital and net operating costs of processes evaluated
Preferential Oxidation	Entire refuse stream	Sulfuric acid	Sulfur is oxidized preferentially without burning excessive amounts of coal. This is done by carefully regulating the quantity of air and controlling the temperature.	Simple process scheme with few operational steps	Treatment removes only a small fraction of organic sulfur and not all pyritic sulfur. Status of development is bench-scale with very limited data. Temperature control problem difficult to solve	No data because of process status

TABLE XXIII

SUMMARY OF PROCESSES FOR UTILIZING COAL REFUSE (CONT'D)

PROCESS	FEED	PRODUCTS	PROCESS DESCRIPTION	ADVANTAGES	LIMITATIONS	ECONOMICS
Two-Stage Gasification	Entire refuse stream	Sulfur Electricity	The gasifier is a specially designed vertical cyclone furnace with two burner ports, one above the other. Refuse burns at the upper port with limited air to produce an H_2S rich gas and slag containing FeS. The slag runs down the walls into the flame at the lower port where refuse is burned with excess air, converting all sulfur compounds to SO_2. Gases passing up through furnace become H_2S-rich. Subsequent treatment recovers sulfur and yields 80-100 Btu/cubic foot fuel gas.	Simple process with efficient recovery of fuel value Produces valuable elemental sulfur	The process is in the concept stage only, no development work has been done.	No data because of process status
Fluid Bed Roasting	Pyrite concentration	Sulfur acid Iron oxides Electric power	Pyrite concentrate is roasted in a fluid-bed furnace to produce SO_2 and a low-sulfur hematitic calcine. SO_2 is converted to acid in a conventional contact plant. Iron ore may or may not be recovered depending upon quality and market. Waste heat can be recovered for process or generation of electricity.	Relatively simple, well-developed technology	Requires pyrite concentration Requires pilot plant development for use with coal refuse Dilution of pyrite with coal causes lower concentration of SO_2 in gas stream. Degree of acid discoloration is unknown.	Low capital cost Net operating cost is encouraging at this stage of development
Outokumpu	Pyrite Concentration	Sulfur Sulfuric acid Iron oxide Electricity	Pyrite is flash smelted by combustion gases which remove the labile sulfur for recovery in elemental form. Other gaseous compounds are catalytically converted to S. Liquid FeS matte is granulated and roasted to give an iron oxide product and SO_2 for conversion to acid.	Recovers about half of the sulfur in elemental form Process developed to commercial scale.	Ash content of coal refuse would cause technical problems Economy would suffer because iron sinter would not be marketable. Requires very large-scale operation.	Not as favorable as conventional fluid-bed process
Orkla	Cupriferous Pyrite	Sulfur	The Orkla process smelts pyrite in a specially designed blast furnace to produce elemental sulfur. Iron, copper, and precious metals report in the matte.	Produces elemental sulfur Process developed to commercial scale	Limited to a lump pyrite feed Modification of technology for feeding coal refuse would be difficult.	No published data It is generally believed to be economic only with a copper product.

Source: Reference 23

included in the economic comparison because of their development status, technical factors, or a combination of the two. The two-stage gasification process was in the concept stage when this study was conducted. The preferential oxidation process had been studied in the laboratory, but exhibited serious technical problems in the control of reaction temperature. The Orkla process was not analyzed further because of its dependency on recovery of copper for overall economic viability, its requirement that finely-divided feed be briquetted, and the technical and economic problems associated with the briquetting operation.

Results of the preliminary analysis are summarized in Table XXIV. This table gives estimated costs and credits which can be presented on a comparable basis for each process. Of particular interest are the figures for "Change in Clean Coal Price," which indicate the effects of these processes on the cost of coal preparation under the assumption that the total costs and credits for processing the pyrite-coal rejects are integrated with the costs of coal preparation.* One of the processes shows a small net credit while four show a net cost ranging from about 12 cents to $1.63 per ton of clean coal.

The annual costs for each process reflect a 20-year depreciation period. Other assumptions relative to production, logistics, marketing, etc., are detailed in Table XXV.

*The economic data presented in Table XXIV should be viewed as relative, not absolute, cost or credit information.

TABLE XXIV
COST EVALUATION SUMMARY

	Combustion - SO_2 Removal	Fluidized Bed Process	Outokumpu Process	Carbonization - Desulfurization	Solvent Extraction
	(figures in thousands except *)				
Capital Investment, $	8,300	2,400 (1)	5,000	14,000	19,500
Total Annual Cost, $/Year	2,201	1,077	1,695	4,006	7,420
Credits for Products (FOB Plant), $/Year	1,160	826	867	2,432	4,368
Credits for Fuel Value, $/Year	1,230	36	60	-	-
Net Annual Cost, $/Year	-189	215	768	1,574	3,052
Change in Clean Coal Price, (2) $/ton*	-0.10	+0.12	+0.41	+0.84	+1.63
Cost of Transporting Products to Market, $/Year	1,275	568	418	1,609	1,407
Selling Cost of Products, $/Year	100	58	61	160	278
Total Cost of Products to Customer at Market, $/Year	2,535	1,452	1,346	4,201	6,053

(1) Facilities include waste heat boilers and acid plant.

(2) Positive values indicated that cost of process exceeds credits from fuel value and products, which results in an increase in clean coal price. Negative values indicate that credits exceed costs, which results in a decrease in clean coal price.

Source: Reference 23 (1968).

TABLE XXV

ASSUMPTIONS FOR PRELIMINARY ECONOMIC ESTIMATES

- Coal Mine: The coal mine produces 2,500,000 tons per year of ROM coal. Mining cost is $3.50 per ton.

- Coal Preparation Plant: The coal preparation plant produces 1,870,000 tons per year of clean coal (1.0% sulfur) at $0.50 per ton. This quality is enough to fuel a 1000 Mw(e) electric power generator.

- Clean Coal: The clean coal has a heating value of 13,750 Btu per pound, a total sulfur content of 1 percent, and an ash content of 4 percent.

- Pyrite-Coal Refuse: A 630,000-ton-per-year stream of pyrite-coal refuse is produced containing 33 percent mineral matter and 67 percent coal. The total pyritic and organic sulfur content is 6.2 percent, and the heating value is 9700 Btu per pound.

- ROM Coal: The ROM coal has a heating value of 13,000 Btu per pound and contains 0.8 percent organic sulfur, 1.5 percent pyritic sulfur, and 10 percent ash.

- Pyritic Concentration: For the processes which require it, a pyritic concentration plant processes 1900 tons per day of pyrite-coal refuse, and produces 110 tons per day of pyrite containing 90 percent FeS_2, 5 percent coal, and 5 percent mineral matter with a pyrite recovery efficiency of 50 percent and a total operating cost of $3.00 per ton of concentrate.

- Capital Costs: Capital costs for the pyrite-coal utilization plant are the installed battery limit costs of the process equipment and auxiliary facilities. The cost of land is not included in the estimate. The installed costs are derived from estimates published in nonproprietary sources using published scale factors to adjust for plant size.

- Utilities: The unit cost of utilities required for operating these processes are:

Cooling Water	$0.05/1000 gallons
Boiler Feedwater	0.50/1000 gallons
Electric Power	0.008/kwhr

TABLE XXV (con't)

ASSUMPTIONS FOR PRELIMINARY ECONOMIC ESTIMATES

- Raw Materials: The unit cost of raw materials required for operating these processes are:

ROM Coal	$3.85/ton-13,000 Btu/lb
	3.50/ton mining cost
Clean Coal	5.50/ton-13,750 Btu/lb
	75% recovery
Pyrite Concentrate	3.00/ton-90% FeS_2
Ash Disposal Cost	0.75/ton

- Labor: Operating labor rates are averaged at $4.00/hr.

- Supervision and Overhead: The prorated cost of supervision, employee benefits, and administrative overhead is equal to operating labor cost.

- Maintenance, Labor, and Material: An amount equal to six percent of plant capital cost is assumed for annual maintenance, labor, and material costs.

- Fixed Capital Charges: The annual fixed charge rate is 15 percent of the pyrite-coal utilization plant capital cost. This includes 20-year depreciation at 6.5 percent interest, property taxes, insurance, and administrative expenses.

- Transporation Costs: The cost of shipping products to a market 200 miles away, based on prevailing railroad point-to-point commodity shipping rates for the various products, is as follows:

Clean Coal (unit train)	$1.44/ton
Coal Extract	2.90/ton
Coal Char	2.90/ton
Iron Oxide	6.25/ton
Sulfur	8.25/ton
Sulfuric Acid	11.00/ton
Sulfur Dioxide	12.00/ton
Light Oil	8.00/ton
Carbon Dioxide	8.00/ton

TABLE XXV (con't)

ASSUMPTIONS FOR PRELIMINARY ECONOMIC ESTIMATES

- By-product Credits: Credits for by-product sale. FOB plant are derived from the prevailing market selling prices for each by-product. The credits are:

Sulfuric Acid (98%)	$16.00/ton	From 500 T/day plant using elemental sulfur at $38.00/ton producing 98% acid
Sulfuric Acid (77.7%)	10.00/ton	From 98% acid at $16.00/ton and discount 20% for quality
Elemental Sulfur	36.30/long ton	Liquid crude, dark sulfur, midwest plant
Coal Extract	6.40/ton	15,800 Btu/lb based on clean coal at $5.50/ton
Char	1.10/ton	8600 Btu/lb based on ROM coat at $3.50/ton and discounted 50% for quality
Fuel Value of Coal Refuse	1.95/ton	9700 Btu/lb
Pipeline Gas	0.26/1000 scf	975 Btu/scf
Light Oil	0.10/gal	Pittsburgh-Midway
Iron Oxide Pellets	13.00/ton	67% Fe
Liquid Carbon Dioxide	15.00/ton	Pittsburgh-Midway and Air Reduction Co.
Steam	0.50/1000 lb	

Source: Reference 23 (1968).

7.2.3 Processes Selected for Detailed Cost Studies

Two of the processes discussed above were selected for further analysis at a more detailed level. The "Fluidized-Bed Pyrite Roasting Process" was examined by A. D. Little, Inc., assisted by Dorr Oliver, and the "Combustion/Sulfur-Oxides-Removal Process" was examined by Bechtel Corporation. Although the fluidized-bed process was an obvious candidate from the outset of the study by virtue of employing proven technology and having been in successful commercial use for roasting of mined pyrites, it was nevertheless included in Bechtel's cost analysis of candidate processes in order to provide a common point of reference for economic comparison with other technically attractive processes. Bechtel's preliminary cost analysis indicated that the Combustion/Sulfur-Oxides-Removal Process and the Fluidized-Bed Pyrite Roasting Process have the most favorable economic prospects in terms of their effect on the price of clean coal. (See Table XXIV.)

These two processes will be discussed separately at greater length later in this chapter. For both, pyritic sulfur is oxidized initially to sulfur dioxide, which is then converted to sulfuric acid. Although both processes produce by-product calcine and can produce a good grade of iron oxide as well as electric power, the major product of both is sulfuric acid. Pertinent market characteristics of this commodity will be discussed in the following section.

7.3 Sulfuric Acid Market Analysis

Sulfuric acid, as an industrial chemical, is a relatively low-cost, heavy commodity. The principal commercial raw material in its manufacture

is elemental sulfur or some sulfur-bearing compound such as pyrite. In 1970, over 85 percent of the sulfur consumed in the United States was used for making sulfuric acid.

There are two features of the sulfuric acid market that warrant special note. One is the large percentage of the market that is captive -- that is, the consumer owns the acid production facilities needed to fulfill his demand. Second is the shipping characteristics of the acid and its raw materials (elemental sulfur and pyrites). Since a ton of sulfur will yield about three tons of acid, it is usually advantageous to ship the sulfur to an acid manufacturing plant near the point of acid consumption rather than ship the acid a great distance.

A different trade-off exists when the source of raw material is pyrite (FeS_2), which in pure form contains about 58 percent sulfur by weight. One ton of pyrite could theoretically produce about 1-1/2 tons of acid, although this theoretical conversion efficiency would probably not be obtained in commercial operation. However, the total coal reject stream is not pure pyrite and even pyrite concentrate from the reject stream may contain significant amounts of other material. This lowers the weight ratio of acid-to-feed even further, and emphasizes the diseconomy of shipping either acid or pyrite-coal over any appreciable distance. In general, shipment of the acid in quantity is limited to 100-200 miles, although there are exceptions to this generality. Another consideration in the use of pyrite for acid manufacture is the

possibility of shipping the solid by-product (iron-bearing calcines) for iron recovery or other disposition.

The production and utilization of sulfuric acid were examined from several points of view. The production and disposition on a regional basis are displayed in Table XXVI. Deposits of coal with high pyritic sulfur content lie primarily in the Mid-Atlantic and East North Central Regions, with additional deposits in Kansas and Missouri (i.e., West North Central Region).

Nationwide consumption of sulfuric acid by end use is indicated in Table XXVII. Projected nationwide growth rates for six major uses are given in Table XXVIII.

In view of the costs of shipping either sulfuric acid or pyrite-coal, it appears that only a limited area of the U.S. could provide a market for acid made from pyrite-coal. The sources of acid demand must be relatively near the sources of high-sulfur coal rejects so that the rejects can serve economically as a raw material for acid. This condition exists to a greater or lesser degree in an eight-state area containing the Northern Appalachian and North Central coal fields. The quantities of acid consumption by end use are given for each of the eight states in Table XXIX. The estimated change in annual rate of consumption is also shown in this table. From the data presented, it is apparent that the use of sulfuric acid for fertilizer manufacture in this geographic area represents the largest end use, about four times as great

TABLE XXVI

ESTIMATED REGIONAL PRODUCTION AND DISPOSITION OF SULFURIC ACID, 1966

(thousands of short tons)

	Production			Disposition		
	New	Refortified	Total	In-Plant	Shipments	Total
New England	205	0	205	95	110	205
Middle Atlantic	3770	260	4030	1487	2543	4030
South Atlantic	9030	0	9030	6791	2239	9030
East North Central	3372	158	3530	1414	2116	3530
West North Central	1103	32	1135	781	354	1135
East South Central	1877	25	1902	514	1388	1902
West South Central	4792	304	5096	1632	3464	5096
Mountain	1834	57	1891	1052	839	1891
Pacific[1]	1523	135	1658	581	1077	1658
Total	27,506	971	28,477	14,347	14,130	28,477

Capacity 1/1/67 34,652

% Operating Rate 82%

[1]Includes one plant in Hawaii

Source: Reference 24 (1968).

TABLE XXVII

SULFURIC ACID DISTRIBUTION BY END USE

(thousands of tons, 100% H_2SO_4)

	1963	1964	1965	1966	% of Total
Phosphate Fertilizers	6906	7753	9275	11675	41%
Ammonium Sulfate	1390	1759	1967	1885	7
Titanium Dioxide	1951	1975	1900	1740	6
Petroleum - Alkylate Refining	1325	1375	1400	1435	5
Petroleum - Other uses[1]	1130	1205	1260	1335	5
Iron and Steel Pickling	1084	1190	1075	1000	3
Hydrofluoric Acid	603	630	710	785	3
Rayon and Cellophane[2]	839	885	895	836	3
Alcohols	599	631	665	700	2
Aluminum Sulfate	536	574	580	592	2
Synthetic Detergents	481	500	510	530	2
Copper & Uranium Leaching & Processing	607	576	567	550	2
Dyes and Intermediates	294	312	330	350	1
Explosives[3]	146	118	100	198	1
Other Chemicals	2697	2951	3099	3389	12
Exports	7	14	7	-	
Miscellaneous	1165	1302	1360	1500	5
Total	21,760	23,750	25,700	28,500	100%

[1]Includes sulfonated petroleum lube oil additives and other petroleum products.

[2]Includes other cellulose film, sheets, or products.

[3]Excludes mixed acid, which is included in other chemicals for 1963, 1964, 1965.

Source: Reference 24 (1968).

TABLE XXVIII
GROWTH IN MAJOR SULFURIC ACID END USES, UNITED STATES
(THOUSANDS OF TONS, H_2SO_4)

	1958	1960	1963	1965	1966	Growth Rate (%/yr) Historical	Projected to 1972
Phosphate Fertilizers	4825	5575	6906	9275	11,675	12%	4-5%
Titanium Dioxide	1375	1500	1951	1900	1740	2-3%*	0
Ammonium Sulfate	1325	1200	1390	1967	1885	5%	5%
Iron & Steel Pickling	750	900	1084	1075	992	0*	--
Rayon & Cellophane	650	700	839	895	836	3%	--
Petroleum Refining	n.a.	n.a.	2455	2660	2770	4%	4%

* Actual use declined in last few years

Source: Reference 24 (1968).

TABLE XXIX
ESTIMATED SULFURIC ACID END-USE PATTERN IN SELECTED STATES, 1966
(THOUSANDS OF SHORT TONS 100% H_2SO_4)

	Pa.	Ohio	Ill.	Ind.	W. Va.	Ky.	Tenn.	Mo.	Area Total	Projected Average Annual Growth Rate
Fertilizers	18	93	1532	47	--	25	126	284	2125	8-10%
Ammonium Sulfate	199	69	28	88	110	15	--	--	509	3
Synthetic Detergents	27	75	30	50	--	--	--	39	221	0*
Titanium Dioxide	--	--	--	--	--	--	--	410	410	0
Aluminum Sulfate	18	28	12	--	--	--	30	30	118	4
Iron & Steel Pickling	142	80	9	105	--	10	--	--	346	0
Rayon & Cellophane	107	--	--	--	150	--	132	--	389	0
Refineries	103	50	102	103	--	--	--	17	375	2
Hydrofluoric Acid	--	30	38	--	40	55	--	--	163	4
Other Uses	146	152	63	23	8	25	50	17	484	5
Total	760	577	1814	416	308	130	338	797	5140	

* Future growth will be in SO_3 sulfonation.

Source: Reference 24 (1968).

as the next largest, and also shows one of the largest projected rates of increase.

The supply-demand situation for sulfuric acid in the states of primary interest is summarized in Table XXX.

7.4 Further Analysis of Two Selected Processes

Two processes were selected from the eight described in Section 7.2 for additional technical and economic analyses. These are the refuse-combustion/sulfur-oxide-removal process and the fluidized bed roasting process. The following discussion will augment the brief description of these processes given in Section 7.2.1.

In the discussions that follow, the technical aspects are discussed separately from the economic aspects, with primary attention given the latter. These discussions present only the economic highlights of each process. More detailed descriptions and analyses of the refuse-combustion/sulfur-oxides-removal process can be found in Reference 23 and of the fluidized bed roasting process in Reference 24.

In conducting the economic studies, both contractors utilized computerized models to investigate the complex relationships among the several variables considered, although somewhat different approaches are used for the two processes. In modeling the refuse-combustion/sulfur-oxides-removal process in which the entire reject stream is burned, the reject stream is considered a source of energy that can be used to meet a given segment of a total (hypothetical) demand for electric power. Recovery of sulfur values in the form of sulfuric acid is an ancillary step

TABLE XXX

SULFURIC ACID SUPPLY-DEMAND SITUATION IN SELECTED STATES, 1966

(thousands of tons, 100% H_2SO_4)

	Estimated Production	Estimated Consumption	Surplus (Deficit)	Capacity to Produce New Acid 1/1/67
Pennsylvania	966	760	206	1040
Ohio	689	577	112	865
Indiana	677	416	261	695
Illinois	1763	1814	(51)	1835
West Virginia	155	308	(153)	156
Kentucky	230	130	100	220
Tennessee	955	338	617	194
Missouri	550	797	(247)	595
Sub-total	5,985	5,140	845	6,320
Other States	22,492	23,330	(838)	28,332
U.S. Total	28,477	28,470	7	34,652

Source: Adapted from Reference 24 (1968).

whereby credits accrue to the overall process through the sale of by-product acid. Additional non-monetary benefit is realized from the attendent reduction in the sulfur oxide content of the combustion gases.

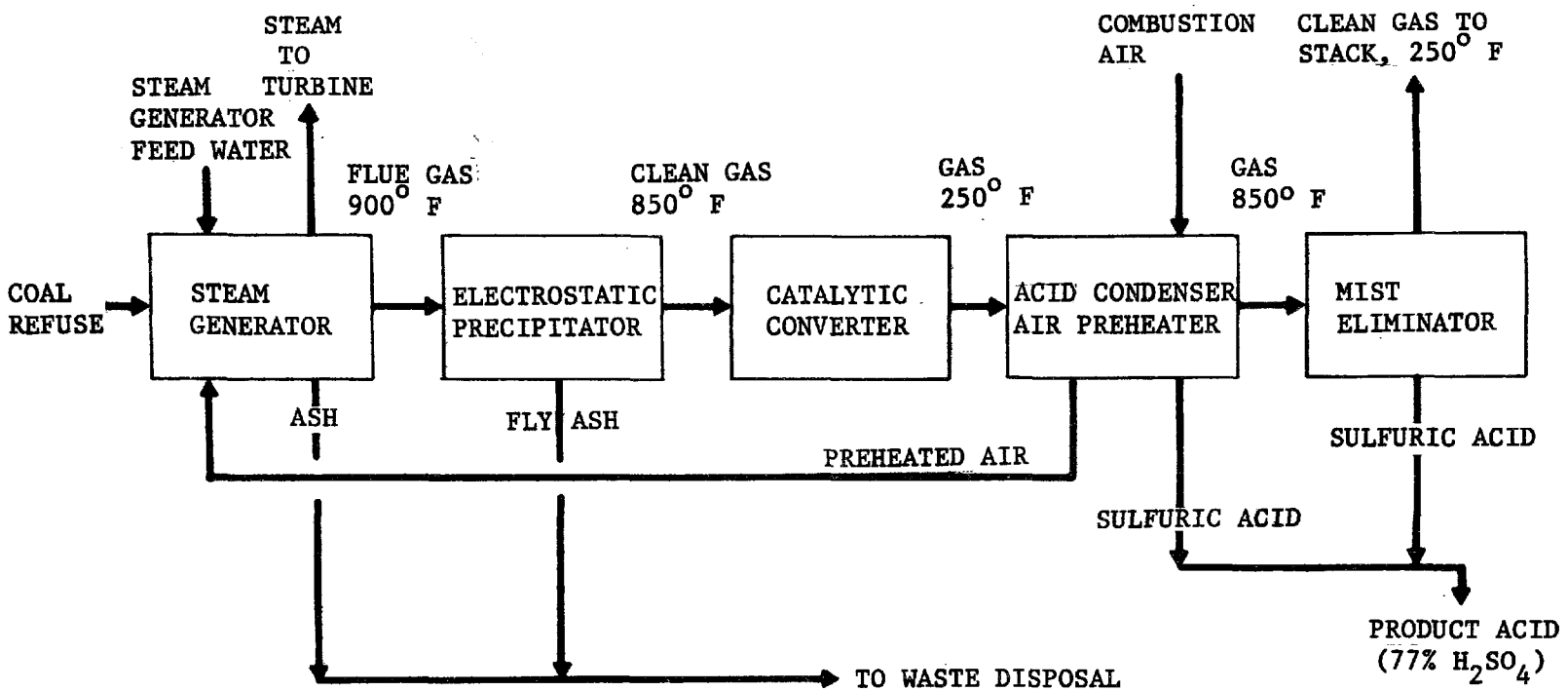
In modeling the economics of the fluidized bed roasting of pyrite concentrate, emphasis was placed on improving the economics of acid production. Although this process can also yield electric power, this was considered a subsidiary product and its production was not included in all of the equipment configurations analyzed.

7.4.1 Refuse-Combustion/Sulfur-Oxide-Removal (Technical Aspects)

The basic steps of this process are: combustion of the refuse stream, steam generation, fly ash removed by an electrostatic precipitator, catalytic oxidation of sulfur dioxide to sulfur trioxide, absorption of sulfur trioxide in water to form acid, concentration of acid, and demisting of stack gas. A flow diagram is given in Figure 26.

Three systems of refuse combustion were considered for use in this process: pulverized refuse, cyclone furnace, and fluidized bed combustion. In the economic analysis presented in Section 7.4.2, equipment cost estimates were developed for a pulverized refuse combustor and a cyclone furnace; the fluidized bed approach was not analyzed for this process since it is treated in detail as a means of roasting pyrite concentrate (Sections 7.4.3 and 7.4.4).

The following processes were considered for processing the sulfur dioxide in the combustion gases:



SOURCE: REFERENCE 23 (1968)

FIGURE 26
REFUSE-COMBUSTION/SULFUR-OXIDES-REMOVAL FLOW CHART

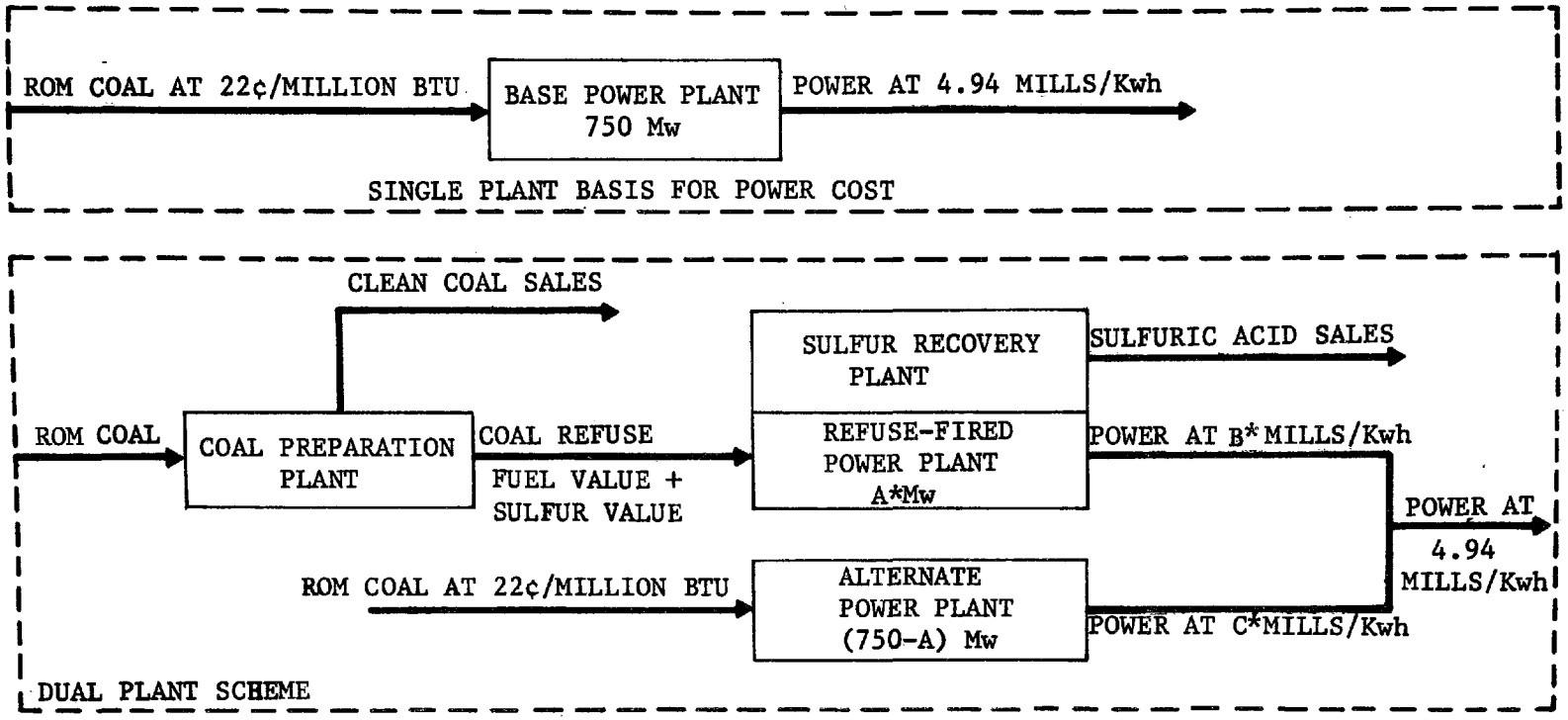
- the Topsoe process;
- the Reinluft process;
- the Wellman-Lord process; and
- the Monsanto catalytic oxidation (Cat-Ox) process.

The Cat-Ox process was selected because of its advanced state of development.

7.4.2 Refuse-Combustion/Sulfur-Oxide-Removal (Economic Aspects)

The economic analysis of the process was made in terms of a scenario in which a given demand for electric power was satisfied in two ways. First, the demand is met conventionally by a single power plant (termed the "base plant") fueled by run-of-mine (ROM) coal. Second, it is met by two smaller plants: one (the "alternate plant") is a conventional steam/electric plant fueled by ROM coal; the other (the "refuse plant") is a combination plant fueled by reject material from a coal preparation plant. The combination plant produces both electric power and sulfuric acid. The nominal total power demand is 750kw. This dual scheme is depicted in Figure 27.

In this analysis, the energy value and the sulfur value of the reject were determined separately. This was done because electric utility companies and non-regulated companies handle their accounting differently and have different views on profitability of investments. These separate components are not reported separately in this summary presentation but are combined to determine total value which is reported as a function of appropriate parameters. For an indication of the distribution of values between these two components, see Figure 31 on page 196.



*Refuse-Fired Plant Generating Capacity (A)
Cost of Poer From Refuse-Fired Plant (B), and
Cost of Power From Alternate Plant (C) are
Variables to be Evaluated.

SOURCE: ADAPTED FROM REFERENCE 23 (1968).

FIGURE 27
DUAL PLANT SCHEME

Interrelations among the following parameters were considered in determining reject value:

- Capacity of the refuse-fueled plant (in terms of electric power output)--shown as A Mw in Figure 27;
- Percent sulfur in reject material;
- Percent ash in refuse;
- Price of sulfuric acid (f.o.b. acid plant);
- Capital cost per kilowatt output capacity.

Using typical ranges of values for the above parameters, Bechtel worked backward to determine the price that a utility using the dual-plant scheme could afford to pay for refuse as fuel. The back-calculation approach was used since it is the most direct, if not the only, method to reflect the economic relationships for a dual-fuel plant with multiple products. By comparing the cost of producing refuse having acceptable energy and sulfur content with the estimated price that a utility could afford to pay for such material, an indication of the market acceptability of refuse as fuel is thereby obtained.

The determination of energy value of the reject material involved the following steps: [23]

1. Establishing load requirement for electric utility (base plant);
2. Estimating power cost for base plant;
3. Establishing capacity of refuse-fired power plant (refuse plant);
4. Establishing capacity factor of refuse plant;
5. Estimating power cost for power plant necessary to supplement refuse plant (alternate plant);

6. Estimating capital cost for refuse plant;
7. Estimating annual operating and maintenance costs for refuse plant;
8. Calculating annual fuel cost for refuse plant;
9. Calculating refuse energy value.

The annual fuel cost for the refuse plant was determined by difference. This procedure involves the premise that the cost of power from the two smaller plants (the refuse plant and the alternate plant) must equal the cost from the base plant. The calculation is as follows:

Base plant total annual cost (including amortization) is equal to the total annual cost of the alternate plant plus the refuse plant.

where:

Refuse plant total annual cost is equal to the annual fixed charges plus the annual operating, maintenance, and fuel costs.

All the above values except the annual fuel cost are calculated when plant sizes and raw coal costs are established. Note that total annual cost includes amortization of capital investment plus all operation and maintenance costs.

A summary of estimated costs for the base plant is given in Table XXXI and for refuse plants of three capacities in Table XXXII. For each refuse plant capacity, separate cost estimates were made for a cyclone-fired steam generator and for a pulverized-fuel-fired steam generator. The estimates for the two types of boilers were essentially the same except those costs related to ash handling, where the differences were

TABLE XXXI

750-MW BASE POWER PLANT SUMMARY

Capacity factor (percent)	75
Annual output (billion kwh)	4.93
Total capital cost (million $)	92.2
($/kw)	122.9
Levelized Annual Cost	
Fixed charges (millions $)	13.0
Operating & Maintenance (millions $)	1.5
Fuel (millions $)	9.8
Total (millions $)	24.3
(mills/kwh)	4.94

Source: Reference 23 (1968).

TABLE XXXII

REFUSE POWER PLANT SUMMARY

		Capacity (Mw)		
		200	300	500
Capacity factor	(percent)	85	85	85
Annual output	(billion kwh)	1.49	2.24	3.72
Total capital cost	(millions $)	37.8	51.1	74.3
	($/kw)	188.8	170.3	148.8
Levelized, annual fixed charges	(millions $)	5.3	7.2	10.5
Annual operating and maintenance costs	(millions $)	0.7	0.9	1.4
(percent of total annual cost)		11.7	10.4	8.9

Source: Reference 23 (1968).

minor, ranging between 1 percent and 3 percent. An average figure for estimated capital costs for each size unit was therefore used for all economic calculations.

Sulfur value of the refuse was determined by a somewhat different procedure which involved back-calculating the price an acid manufacturer could afford to pay for various grades of reject material in order to achieve a given return on investment for varying levels of manufacturing expense, production capacity, and product acid price. The steps in this procedure are outlined below:[23]

1. Estimate capital cost of the sulfur recovery plant for a specific refuse plant capacity;
2. Establish method of financing;
3. Establish discounted rate of return on equity investment and calculate discounted equity investment;
4. Establish refuse type and sulfuric acid price (f.o.b. acid plant;
5. Calculate annual revenue;
6. Estimate annual operating cost less price paid for refuse;
7. Establish depreciation method and calculate annual income tax, other taxes, investment tax credit, interest, and debt service payments;
8. Calculate refuse sulfur value.

Investment costs attributable to sulfur recovery are summarized in Table XXXIII. These cost estimates were based upon a scaling down of

TABLE XXXIII

SULFUR RECOVERY PLANT INVESTMENT

		Refuse power plant net capacity (Mw)		
		200	300	500
Fixed capital cost	(millions $)	8.3	11.4	17.2
Working capital	(millions $)	0.4	0.6	0.9
Interest during construction[1]	(millions $)	0.5	0.7	1.0
Total investment	(millions $)	9.2	12.7	19.1
	($/kw)	45.9	42.3	38.2
Loan[2]	(millions $)	2.6	3.6	5.4
Equity investment	(millions $)	6.5	9.0	13.6
Discounted rate of return	(percent)	12.5	12.5	12.5
Discounted equity investment	(millions $)	5.1	7.1	10.6

[1] 6 percent interest for three years-period of construction

[2] 30 percent of fixed and working capital

Source: Reference 23 (1968).

more detailed cost estimates for applying a catalytic oxidation type of process to a 1000 megawatt conventional coal-fired plant.

The operations of the refuse power plant and the sulfur recovery plant are, of course, not independent. Certain equipment is shared between the two operations; other equipment (such as blowers and precipitators) needed for either operation must be larger to meet the needs of both. Similarly, operational costs are mutually interdependent. For example, high sulfur concentrations that are advantageous for acid production result in increased costs for operating the refuse-fired power plant (assuming a constant level of power output). The effects of such interdependencies were taken into account in establishing the values of energy and sulfur in the fuel.

Total refuse value was determined by combining the values attributable to energy content and sulfur content. This combined value is affected by a variety of economic and operating conditions, and is reported as a function of:

- capacity of refuse power plant;
- sulfur content of refuse;
- ash content;
- sulfuric acid sale price (77 percent H_2SO_4);
- plant investment per unit of output;
- rate of return on investment.

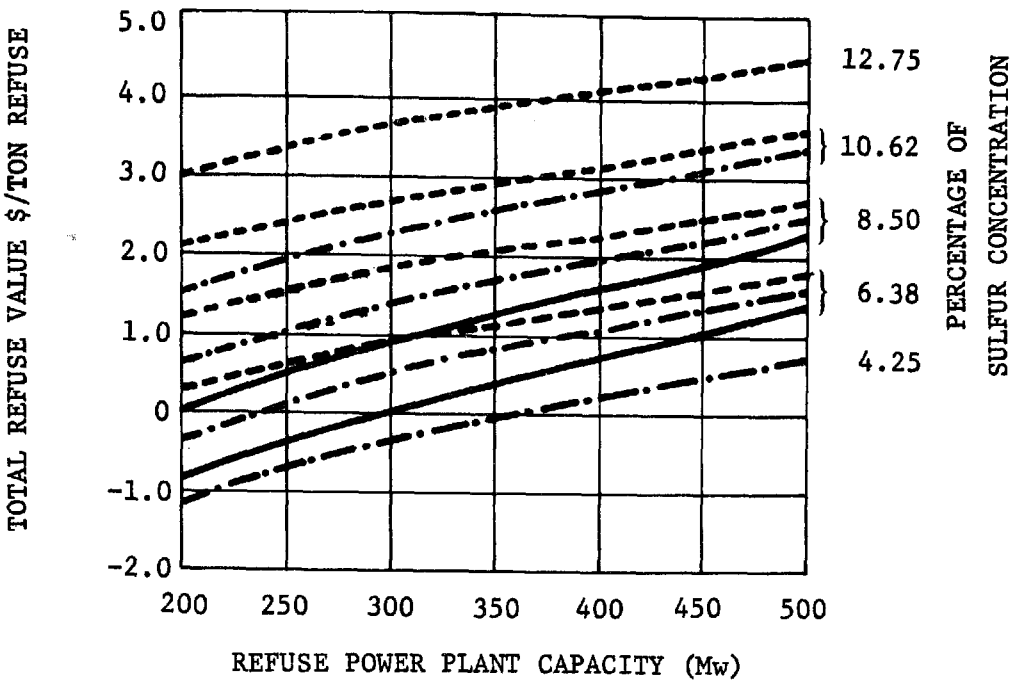
When total value of the refuse is determined on a unit weight basis, its effect on the value of cleaned coal can be determined from the percentage yield of the coal preparation operation.

Because of the number of variables affecting refuse value, results are presented in some 17 separate graphs. These will not be reproduced in total, but the more important ones are presented here. All dollar figures shown reflect 1967-1968 costs, expenses, taxes, and dollar values. It should be noted that the total reject (refuse) values presented here represent the value of refuse at the refuse-fired power/acid plant, and thus include any costs for transporting the refuse from the coal preparation plant to the refuse-fired power plant.

Figure 28 shows refuse value as a function of plant capacity for each of three levels of sulfur content and three levels of ash percentage. All of these values assume an acid selling price of $12.50 per ton f.o.b. plant. Refuse values are seen to range from a negative value of $1.00 per ton (meaning that a loss would be incurred in the power generating and acid producing operations) under conditions of low sulfur content and a very small (200 mw) refuse plant to a positive $4.50 per ton for a high sulfur refuse being burned in a large (500 mw) plant. The graph also indicates that some reduction in coal preparation costs can be achieved for any refuse (pyritic) sulfur content over 8.5 percent, irrespective of ash content in the refuse.

For a 300 mw refuse power plant burning reject material with 34 percent ash, Figures 29, 30, 31, and 32 respectively illustrate the effects of the following parameters on both the reject (refuse) value and the concentration of sulfur in the refuse:

- sulfuric acid price;



PERCENTAGE OF
ASH CONCENTRATION

- - - - 42.5

—·—·— 34.0

——— 25.5

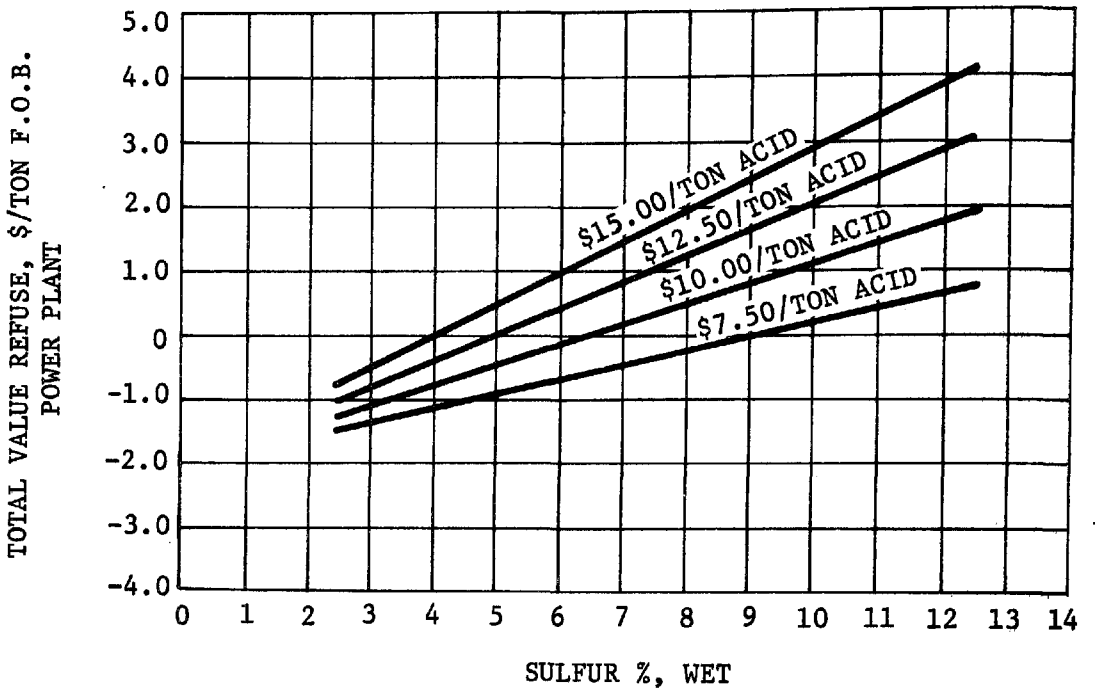
NOTES:

1. BASE POWER PLANT CAPACITY = 750 Mw
2. BASE POWER PLANT CAPACITY FACTOR = 85%
3. SULFURIC ACID PRICE = $12.50/TON
4. REFUSE MOISTURE = 15.0%

SOURCE: REFERENCE 23 (1968)

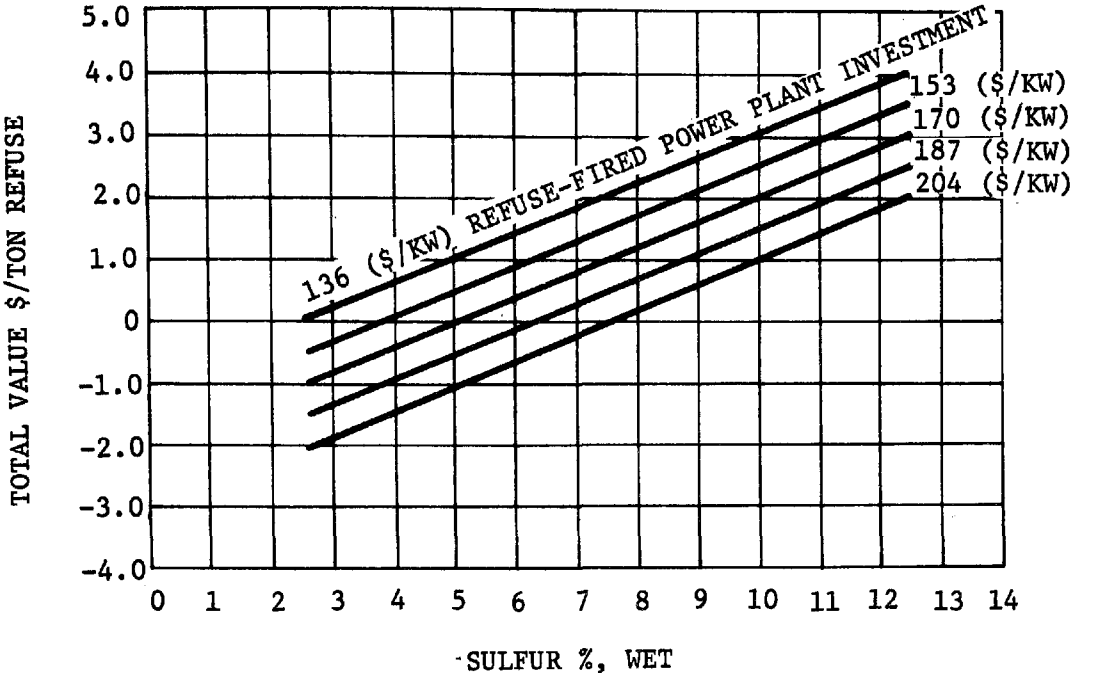
FIGURE 28

TOTAL REFUSE VALUE–REFUSE POWER PLANT CAPACITY–REFUSE COMPOSITION



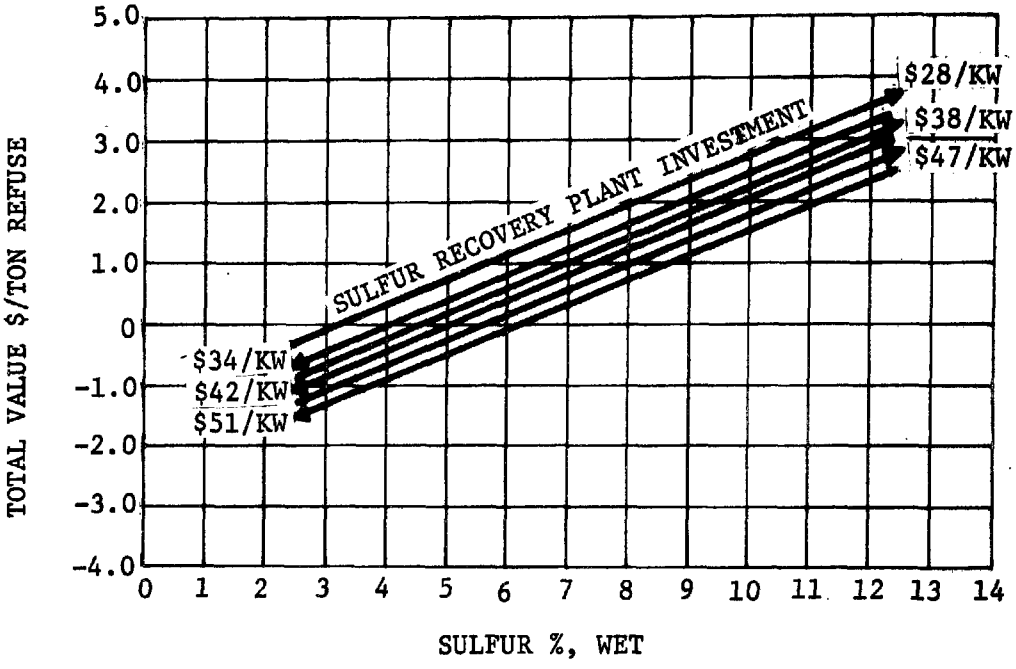
SOURCE: REFERENCE 23 (1968)

FIGURE 29
TOTAL REFUSE VALUE–REFUSE SULFUR CONCENTRATION–
SULFURIC ACID PRICE (REFUSE ASH CONCENTRATION, 34.0%)



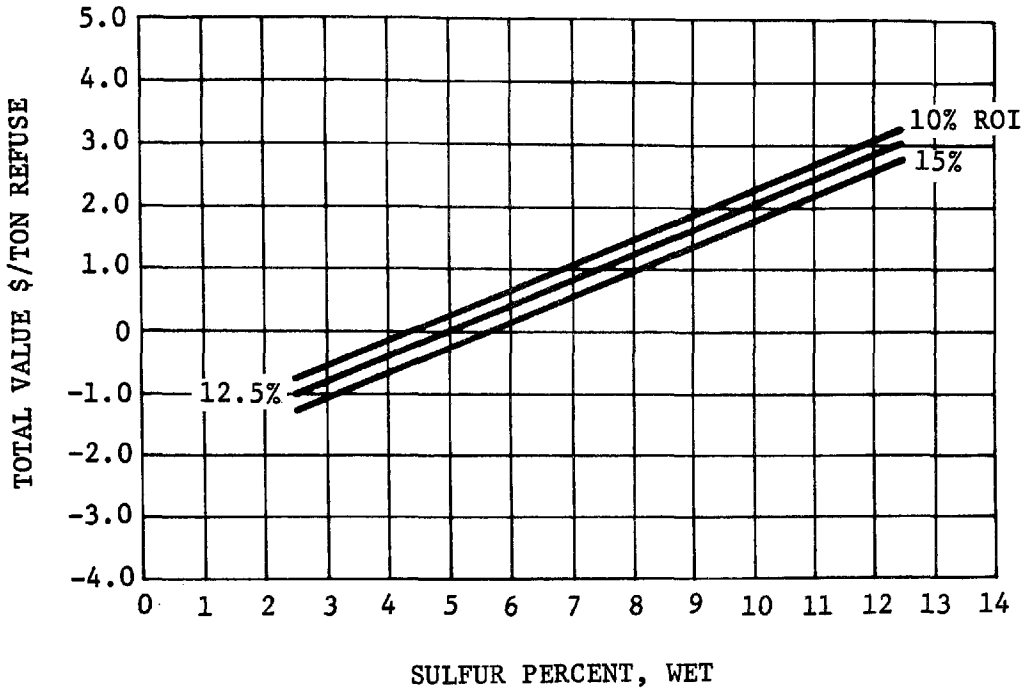
SOURCE: REFERENCE 23 (1968)

FIGURE 30
TOTAL REFUSE VALUE-REFUSE SULFUR CONCENTRATION–REFUSE POWER PLANT CAPITAL COSTS (REFUSE ASH CONCENTRATION, 34 PERCENT; SULFURIC ACID PRICE, $12.50/TON)



SOURCE: REFERENCE 23 (1968)

FIGURE 31
TOTAL REFUSE VALUE-REFUSE SULFUR CONCENTRATION–SULFUR RECOVERY PLANT INVESTMENT (REFUSE ASH CONCENTRATION, 34 PERCENT; SULFURIC ACID PRICE, $12.50 TON)



SOURCE: REFERENCE 23 (1968)

FIGURE 32

TOTAL REFUSE VALUE-REFUSE SULFUR CONCENTRATION-RATE OF RETURN ON INVESTMENT (REFUSE ASH CONCENTRATION, 34 PERCENT; SULFURIC ACID PRICE, $12.50/TON)

- refuse power plant capital cost;
- sulfur recovery plant investment;
- rate of return on investment.

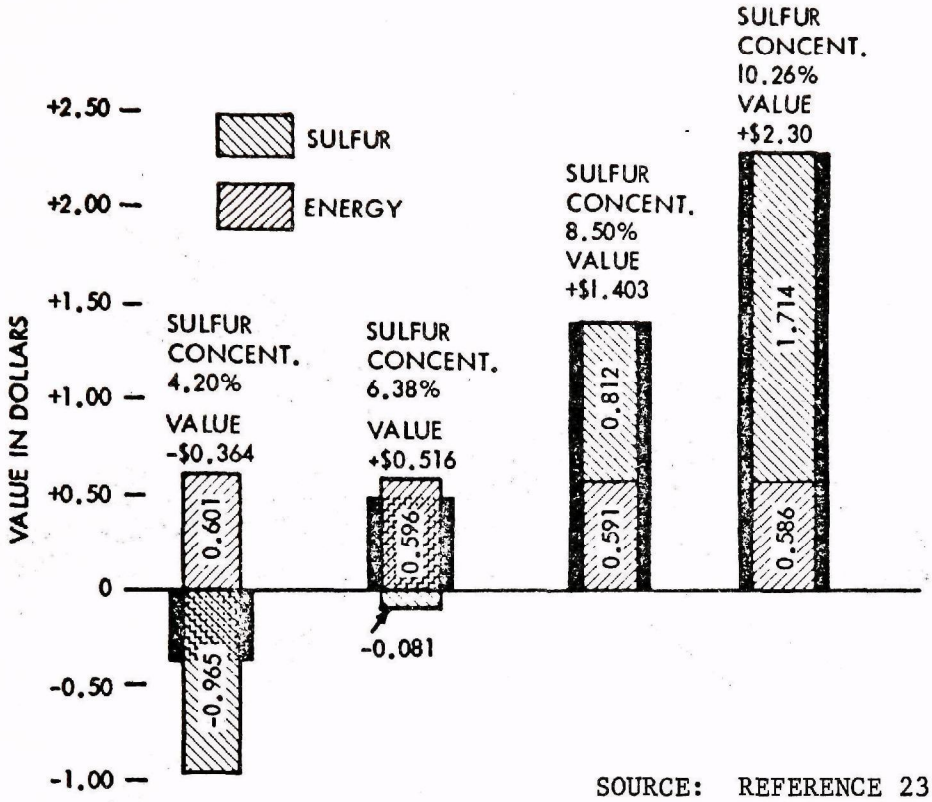
The distribution of total refuse value between the energy component and sulfur component for four levels of sulfur content is shown in Figure 33 for a 300 mw refuse plant fired with a reject material containing 34 percent ash.

Figure 34 graphically illustrates the relative importance of the variables that affect total refuse value. The origin (0, 0 coordinates) of this figure represents the specified standard conditions given in Table XXXIV, the abscissa represents the percent change in a single independent variable; and the ordinate is the resulting incremental change in total refuse value. Although this chart was based on a 300 mw refuse-fired power plant, the conclusions that may be drawn from this graph are generally true for other sizes.

The chart shows that refuse value is most sensitive to change in acid price and capital cost of the refuse-fired power plant. For example, a 10% increase in acid price nearly offsets a 10% increase in refuse plant investment.

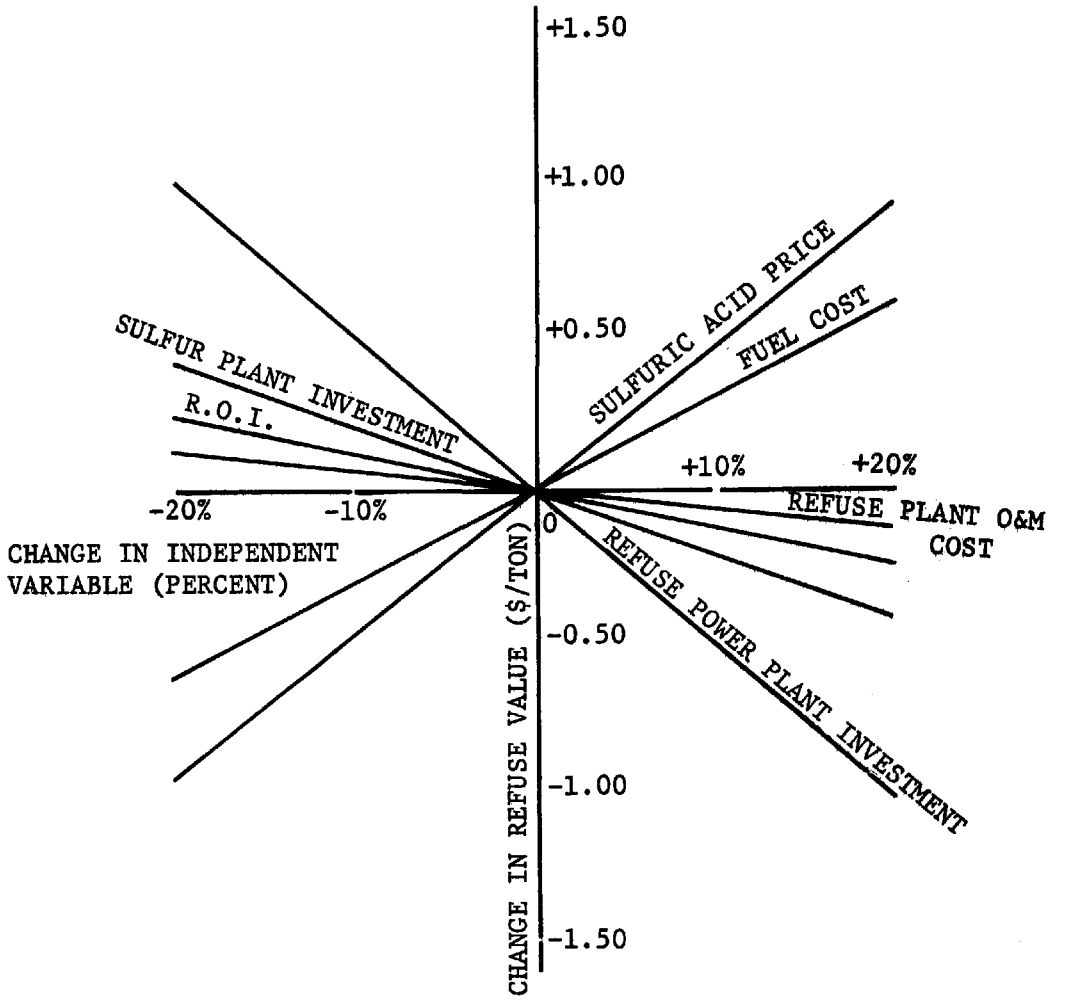
7.4.3 Fluidized Bed Roasting of Pyrite, followed by Catalytic Oxidation of Sulfur Dioxide - (Technical Aspects)

This process requires a feed of considerably higher pyrite content than the reject stream ordinarily produced by coal preparation. Hence an additional operation is required to concentrate the pyrite in the



SOURCE: REFERENCE 23 (1968)

FIGURE 33
TOTAL REFUSE VALUE COMPONENTS (300 Mw REFUSE POWER PLANT; REFUSE ASH CONCENTRATION, 34 PERCENT)



SOURCE: REFERENCE 23 (1968)

FIGURE 34

TOTAL REFUSE VALUE SENSITIVITY, 300-MW REFUSE POWER PLANT

TABLE XXXIV

STANDARD CONDITIONS

300-MW REFUSE POWER PLANTS

I. Base Power Plant

Net capacity	750 Mw
Capacity factor	75 percent
Annual output	4.93 billion/kwh
First year fuel cost	19.8 cents/million Btu
Fuel cost escalation	1.5 percent/yr.

II. Alternate Power Plant

Net capacity	450 Mw
Capacity factor	68 percent
Annual output	2.70 billion/kwh
First year fuel cost	19.8 cents/million Btu
Fuel cost escalation	1.5 percent/yr.

III. Cost Refuse Power Plant

Net capacity	300 Mw
Capacity factor	85 percent
Annual output	2.24 billion kwh
Total capital cost	$51.1 million
	170.3 $/kw

IV. Sulfur Recovery Plant

Total investment	$12.7 million
	42.3 $/kw
Discounted rate of return	12.5 percent
Debt financing	30 percent

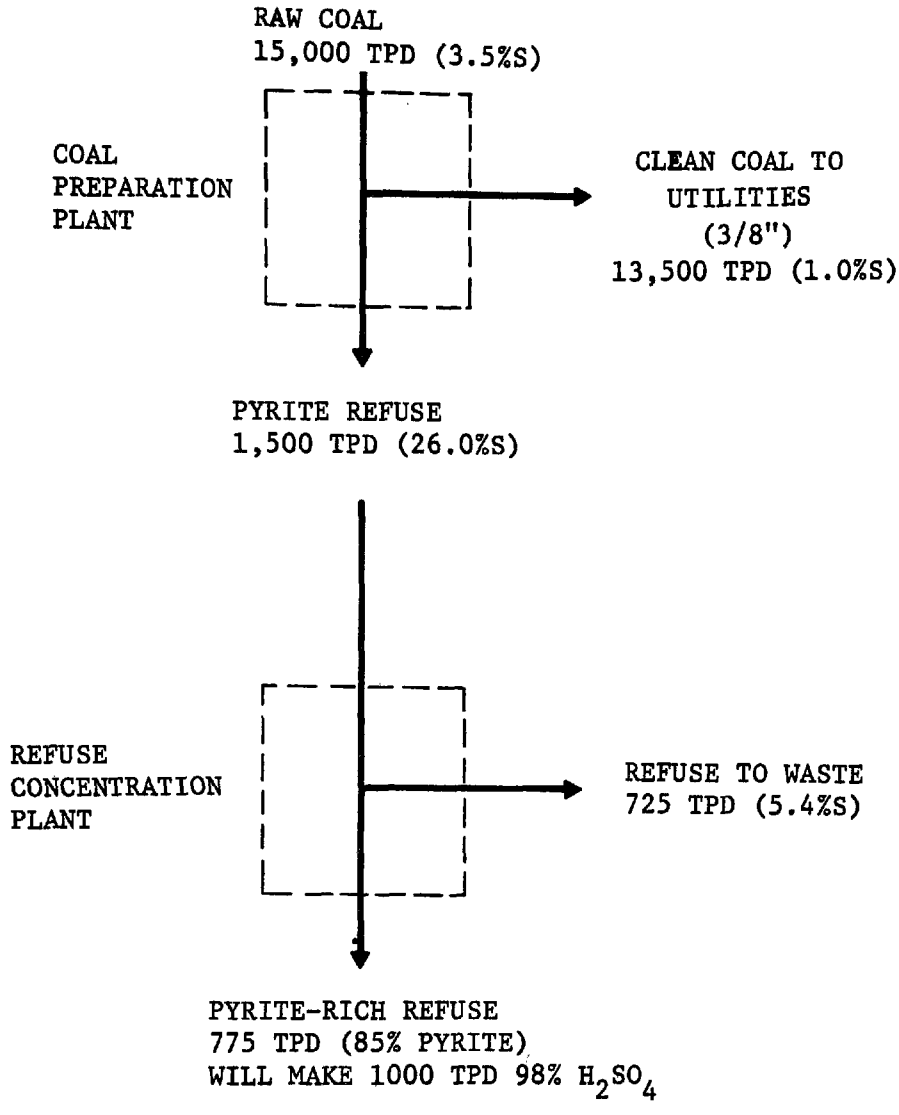
Source: Adapted from Reference 23 (1968).

reject component to be roasted. The two cleaning and concentrating operations are shown schematically in Figure 35. The quantities shown in this figure indicate the approximate processing rates needed to produce 13,500 tons per day of clean coal and 1000 tons per day of 98 percent sulfuric acid.

The following comments on the fluidized bed roasting process supplement and expand upon the description of this process presented in Section 7.2. A flow diagram of the basic process yielding sulfuric acid is shown in Figure 36. The major processing steps are:

- roasting the pyrite in a fluidized bed (where the crushed pyrite is "fluidized" by air blown through multiple openings in the floor of the bed and forced upward through the layer of crushed pyrite), to yield heat, combustion gases, and calcine;
- generation of steam, then electric power, from heat produced in the roasting operation;
- recovery of sulfur oxides from the combustion gases;
- catalytic oxidation of sulfur dioxide to form sulfur trioxide;
- absorption of sulfur trioxide in water to form sulfuric acid;
- concentration of the sulfuric acid to commercial densities.

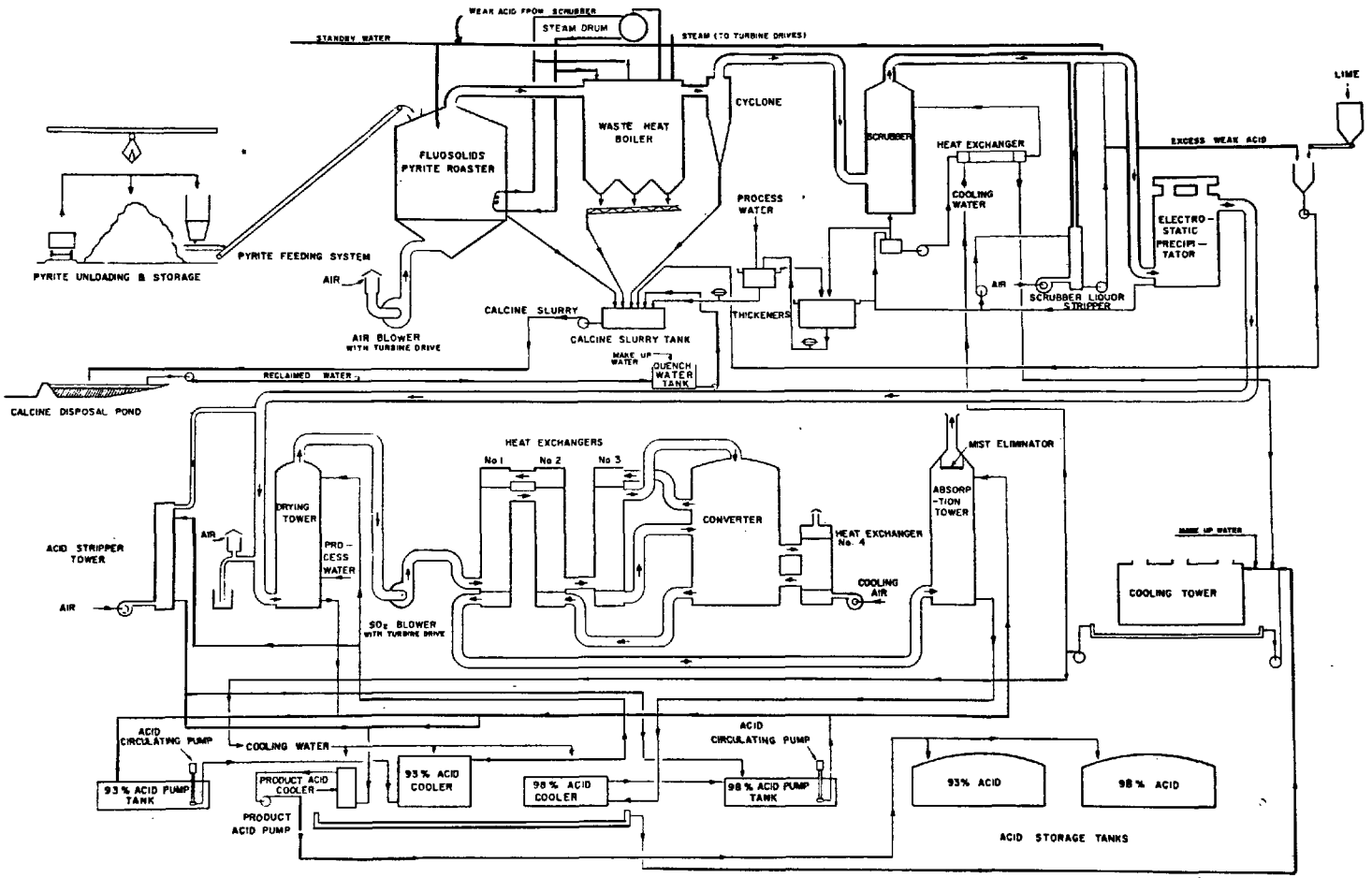
In some locations, an additional major step is added; the recovery of iron oxides for use in steelmaking. Preliminary analyses indicate that recovery of iron values would not be economic in most geographic areas of the U.S. where sulfuric acid is likely to be manufactured from



TPD = TONS PER DAY

SOURCE: REFERENCE 24 (1968)

FIGURE 35
PYRITE–REMOVAL PROCESS



SOURCE: REFERENCE 24 (1968)

FIGURE 36

FLOW DIAGRAM OF FLUOSOLIDS PYRITE-ROASTING/ SULFURIC-ACID PLANT PLANT TYPE I-A

pyrites, hence credits for iron are not claimed in the economic analyses that follow and the recovery of iron is not included in the technical description of the process.

There are several options as to the type of ancillary equipment that might be included with the basic fluidized bed plant for pyrite roasting and acid manufacture. The steam/electric generator is advantageous in some cases, as when the acid plant is integrated with other types of chemical works or located in an area with high electric power costs, but this is not generally the case. Also, cooling towers can be used to reject waste heat to the atmosphere rather than to a nearby river, but this additional item of equipment would not be required in some locations (at least it was not in 1968, when this study was completed). Consequently, several alternative equipment configurations can be assumed for the basic plant. The following alternatives were evaluated:

- plant with steam generator and cooling tower (designated in the following tables as Type I-A plant);
- plant with steam generator but no cooling tower (Type I-B);
- plant with cooling tower but no steam generator (Type II-A);
- plant with neither steam generator nor cooling tower (Type II-B).

Any of the above types of plants could be utilized as a stand-alone installation producing sulfuric acid and, in some cases, electric power, as the principal product(s). Alternatively, they could be integrated with other chemical processes to make quite different products, one of

the more commercially attractive being phosphate fertilizer. This represents another type of option in plant configuration. When integrated in this manner electric power produced by a steam generator heated by the roaster can generally be utilized advantageously by various steps in the overall operation.

One possible additional method is oxygen enrichment. This approach might be used for roasting low-grade (high coal content) pyrite to produce high strength SO_2 gas for the manufacture of acid. By virtue of less nitrogen dilution, oxygen enrichment would make it possible to produce a gas of higher SO_2 content.

To evaluate the merits of oxygen enrichment a process and economic study was performed as follows. Consider a pyrite roasting-contact sulfuric acid plant designed to process pyrite plant feed of a specified composition (for example, composition No. 2* which contains 90 percent pyrite, 5 percent coal, 5 percent inerts). By adding the appropriate amount of oxygen to the air, lower-grade pyrite-feeds can be processed in this plant with no increase in gas volume or no decrease in sulfur dioxide concentration in the gas. Maintaining this level of sulfur dioxide concentration would permit utilization of conventional equipment in the subsequent conversion of sulfur dioxide to sulfuric acid. This is one of the real advantages of the use of pure oxygen.

If the total processing costs for pyrite plant feed composition No. 2 are used as a basic standard and to these costs are added the oxygen

*See Tables XXXV and XXXVI for the ranges of feed compositions examined in the A.D. Little study.

costs, the resultant total should represent a reasonable approximation of the total processing costs for an oxygen enrichment plant. The resulting cost total indicates that the use of oxygen to enrich the air is not an economical approach to reducing the processing costs. A possible reduction in processing cost is indicated only for large tonnage, 1500-2500 tons of acid per day, and for pyrite plant-feed composition numbers* 10 and 12. However, for these low-grade pyrite feeds, the total processing costs (with or without oxygen enrichment) make the whole project economically questionable. Furthermore, a technical problem with the roaster heat balance and removal of excess heat for these lower-grade feeds has not been resolved.

In the roasting or oxidation of any particular pyrite-coal material a certain amount of heat is generated over and above that required to maintain the roasting reaction at the desired temperature level. With oxygen-enriched air, the volume of product gas resulting from oxidation of the feed is less than with air only. As a result, less heat is removed as sensible heat in the product gas and, therefore, more of the excess heat must be removed by steam-generating bed coils or by water injection. As the grade of pyrite feed decreases (less pyrite, more coal) this generation of excess heat becomes more of a problem. At some point along the line of decreasing feed grade it becomes no longer possible to place a steam-generating coil with sufficient heat-absorbing capacity in the fluid bed. Instead, it becomes necessary to increase

*See Tables XXXV and XXXVI for composition of the various feeds

materially the number of lines of roasters required for a given production capacity. This increases both capital costs and operating costs. For a plant that uses water or weak acid for removal of excess heat and for control of roasting temperature, the amount of additional water or weak acid required for a plant employing oxygen enrichment substantially increases the roaster exit-gas volume. This, in turn, requires larger and more expensive gas cooling and cleaning equipment. For these technical reasons the possible use of oxygen, even for large tonnages, is not a solution for reducing processing costs.

The use of oxygen instead of secondary air in the acid plant, to supply the oxygen required for SO_2 oxidation, might be considered as an alternative to using oxygen-enriched air for the pyrite roaster. This approach would have the following effect upon the process: (1) the total oxygen requirement would be less but this oxygen, because of the lower demand, would be more expensive per pound; (2) the pyrite roasting plant would not benefit by reduced equipment size, and (3) the acid plant would benefit by the use of oxygen in place of secondary air from the standpoint of the acid-plant water balance and the heat balance. Without going into detailed process calculations or plant cost data, it is believed quite likely that the use of oxygen in place of secondary air would show less economic benefit than if oxygen were used to enrich the air to the pyrite roasters.

A more practical approach might be to consider the possibility of adding both elemental sulfur and oxygen to the roaster as a means of

decreasing the processing costs. Additional technical and economic analysis would be required to determine the possible merits of this approach.

7.4.4 Fluidized Bed Roasting of Pyrite Concentrate (Economic Aspects)

The economic analysis of this recovery system considered that each of the following parameters could take on a range of values:

- Composition of the feed (in terms of percent pyrite, percent coal, and percent gangue);
- Plant capacity (tons of sulfuric acid per day);
- Price of elemental sulfur;
- Market for sulfuric acid;
- Proximity of pyrite source to acid market;
- Rate of return on investment.

The analysis determined values of the following variables for various combinations of the above parameters (not all parameters were used in each economic determination):

- Battery limit costs and total capital investment for various acid plant types;
- Total processing costs for various plant types;
- Prices that could be paid for pyrites to keep manufacturing costs of sulfuric acid made from pyrites competitive with acid made from elemental sulfur;

- Prices that could be paid for pyrites (f.o.b. coal preparation plant) to compete with elemental sulfur for manufacture of sulfuric acid as part of an integrated operation to produce phosphatic fertilizer.

Results from the above cost determinations are presented in the following discussion.

Capital costs for the various types and sizes of plants were estimated on the basis of a complete plant being constructed from the ground up. Battery limit costs include purchase and erection of all processing equipment including:[24]

(1) Calcine disposal and neutralized waste acid disposal equipment;*

(2) Liming station for neutralization of waste acid;

(3) Boiler-feed water-treatment equipment (for Plant Type I);

(4) Motor-control center, including switch gear and starters;

(5) Open (on the ground) storage for one month's supply of pyrite feed;

(6) Storage for seven days' production of acid in two or more tanks;

(7) Operating-control room and such other housing as required to protect such non-weatherproof equipment as instruments, motor-control center, etc. that are a part of the process facilities; and

(8) Water-cooling tower with air-circulation fans and water pumps (for Plant Type I-A and II-A).

*For the purposes of this report, the investment and operating costs of calcium disposal facilities were assumed to be the same as would be required if the calcines were sold as a sinter strandfeed material.

Total plant costs were obtained by increasing the battery limit costs by a given percentage to cover offsite facilities such as land, power substation, water supply and sewers, roads, fencing, etc. This percentage increase was 18 percent for plants with steam/electric generating equipment and 20 percent for plants without this equipment.

Total capital investment was obtained by increasing the total plant costs by 11 percent to cover construction and startup (interest on construction money, taxes, insurance during construction, starting personnel training, etc.).

For determining plant costs, the following factors were treated as parameters:

- plant capacity (tons per day of product acid);
- plant type (with or without steam generation equipment or cooling tower);
- pyrite feed composition.

Estimated costs of plants reflecting various values of these parameters are given in Table XXXV. The range of values considered for each parameter is shown in the table. Total capital investments for plants meeting this range of parameter values vary from $3.7 million for a Type II-B plant of 258 tons/day capacity using No. 2 pyrite feed to $35.5 million for a Type I-A plant of 2500 tons/day capacity using No. 12 pyrite feed.

Total operating costs were determined for plants covering the same range of parameter values as used for capital cost determination.

TABLE XXXV
BATTERY LIMIT COSTS AND TOTAL CAPITAL INVESTMENT VS. CAPACITY AND FEED CONSUMPTION
(MILLIONS OF DOLLARS)

Capacity Factors (See Table 6)		Pyrite Plant Feed Composition Numbers											
		2		4		6		8		10		12	
		1.0		0.897		0.833		0.783		0.673		0.530	
Plant Type 1A — Steam, Cooling tower		Bat. Lim. Cost	Tot. Cap. Invest.	Bat. Lim. Cost	Tot. Cap. Invest.	Bat. Lim. Cost	Tot. Cap. Invest.	Bat. Lim. Cost	Tot. Cap. Invest.	Bat. Lim. Cost	Tot. Cap. Invest.	Bat. Lim. Cost	Tot. Cap. Invest.
TPD Capacity	TPY (98%) Acid									Approx.		Order of Mag.	
250	82500	3.16	4.14	3.52	4.60	3.80	4.98	4.04	5.29	4.69	6.14	5.96	7.83
500	165000	4.19	5.48	4.67	6.10	5.03	6.59	5.35	7.00	6.21	8.15	7.91	10.31
1000	330000	6.97	9.12	7.75	10.19	8.35	10.96	9.92	11.66	10.30	13.53	13.17	17.20
1500	495000	9.21	12.10	10.26	13.50	11.04	14.54	11.78	15.42	13.67	17.95	17.40	22.80
2500	825000	14.39	18.86	16.04	21.00	17.30	22.65	18.37	24.10	21.40	28.00	27.20	35.50
Plant Type IB — Steam, No cooling tower													
TPD Capacity	TPY (98%) Acid												
250	82500	3.11	4.07	3.47	4.54	3.74	4.88	4.06	5.20	4.61	6.05	5.80	7.60
500	165000	4.11	5.39	4.59	6.00	4.93	6.46	5.26	6.87	6.11	8.00	7.78	10.15
1000	330000	6.85	8.96	7.65	10.00	8.22	10.76	8.75	11.46	10.16	13.31	12.95	16.91
1500	495000	9.06	11.89	10.10	13.24	10.86	14.27	11.56	15.18	13.46	17.65	17.11	22.40
2500	825000	14.18	18.55	15.96	20.70	17.05	22.25	14.21	23.70	21.00	27.55	26.80	35.00
Plant Type IIA — Cooling tower, No steam													
TPD Capacity	TPY (98%) Acid												
258	85000	2.87	3.82	3.20	4.27	3.44	4.58	3.66	4.88	4.26	5.67	5.44	7.25
517	170600	3.76	5.00	4.18	5.58	4.50	6.00	4.78	6.38	5.56	7.51	7.10	9.45
1033	340900	6.05	8.05	6.75	8.98	7.26	9.68	7.73	10.30	8.98	11.94	11.43	15.24
1550	511500	7.89	10.50	8.79	11.70	9.48	12.61	10.10	13.45	11.70	15.60	14.88	19.80
2583	852000	12.12	16.15	13.50	17.98	14.55	19.37	15.49	20.60	18.00	24.00	22.86	30.40
Plant Type IIB — No cooling tower, No steam													
TPD Capacity	TPY (98%) Acid												
258	8500	2.76	3.67	3.07	4.08	3.30	4.39	3.52	4.68	4.09	5.44	5.22	6.93
517	170600	3.60	4.80	4.01	5.34	4.32	5.75	4.59	6.10	5.35	7.12	6.80	9.04
1033	340900	5.81	7.73	6.48	8.63	6.95	9.25	7.42	9.87	8.60	11.45	10.98	14.60
1550	511500	7.57	10.08	8.44	11.20	9.09	12.10	9.66	12.88	11.22	14.99	14.31	19.10
2583	852000	11.71	15.65	13.03	17.37	14.05	18.73	14.95	19.90	17.35	23.12	22.10	29.40

Plant Type
- I-A Cooling tower and steam generation equipment.
- I-B Steam generation equipment but no tower.
- II-A Cooling tower, no steam generation equipment.
- II-B No cooling tower, no steam generation equipment.

Plant Feed Composition No.	%Pyrite	%Coal	%Gangue
2	90	5	5
4	80	7	13
6	85	10	5
8	70	10	20
10	70	15	15
12	65	23	12

SOURCE: REFERENCE 24 (1968)

Operating costs include direct costs (power, fuel, water, chemicals, maintenance supplies, operating and maintenance labor, etc., but not pyrite feedstock) and indirect costs (managerial and administrative expense, office services and supplies, non-plant maintenance, sales expense, taxes, insurance, depreciation, etc.). Total operating cost are presented in Table XXXVI. The following direct and indirect costs (and credits) were explicitly excluded:

- Cost of purchasing or processing pyrite feedstock;
- Cost of transporting pyrite to acid plant;
- Cost of shipping product acid;
- Credit for by-product steam, electric power, calcines, or iron oxide (credits for these by-products were estimated but not reflected in this table because of uncertain markets for these items at the probable locations of pyrite-coal acid plants);
- Indirect credit for increased value of beneficiated coal or decreased disposal cost of cleaning plant reject material.

It should be noted that operating cost estimates for plants using No. 10 and No. 12 feed (with low sulfur content and low sulfur-to-carbon ratios) are of lower accuracy than the other estimates in the table. Considering only the range of feedstocks from No. 2 to No. 8 for which firm estimates are available, the plant operating costs vary from $5.51 to $20.81 per ton of product acid. Some of these operating costs for smaller plants are expressed as costs per ton of product, and exceed the estimated selling price of acid in the area under study in the 1967-1968 time frame.

TABLE XXXVI
TOTAL PROCESSING COSTS (DIRECT & INDIRECT COSTS) (DOLLARS PER TON OF 98% PRODUCT ACID) VS. PYRITE PLANT FEED COMPOSITION AND PLANT CAPACITY

Pyrite Plant Feed Composition and Plant Capacity

	2		4		6		8		10		12	
%Pyrite	90		80		85		70		70		65	
%Coal	5		7		10		10		15		23	
%Inerts	5		13		5		20		15		12	
S/C Ratio	13.8		8.7		6.5		5.36		3.58		2.2	
S/H_2 Ratio	182		116		86		71		47.5		29	
Plant Type →	IA	IIA	IA	IIA	IA	IIA	IA	IIA	IA	IIA	IA	IIA
Plant Capacity - TPD (98%) Acid									Approx.		Order of Mag.	
Plant Type I / Plant Type II												
250 / 258	18.11	15.63	18.92	16.57	19.59	17.17	20.11	17.73	21.61	19.23	24.53	22.21
500 / 517	10.74	9.47	11.34	10.08	11.76	10.52	12.15	10.90	13.66	12.62	15.74	14.65
1000 / 1033	7.75	6.92	8.27	7.43	8.63	7.82	9.31	8.46	10.22	9.41	12.29	11.62
1500 / 1550	6.60	5.92	7.07	6.38	7.63	7.00	7.90	7.32	8.97	8.35	11.53	10.76
2500 / 2583	6.20	5.51	6.88	6.20	7.20	6.53	7.72	7.03	8.74	8.02	11.14	10.32
Plant Type →	IB	IIB	IB	IIB	IB	IIB	IB	IIB	IB	IIB	IB	IIB
Plant Capacity - TPD (98%) Acid									Approx.		Order of Mag.	
Plant Type I / Plant Type II												
250 / 258	18.64	16.62	19.54	17.54	20.21	18.23	20.81	18.84	22.42	20.52	25.40	23.80
500 / 517	11.33	10.44	11.97	11.14	12.47	11.67	12.88	12.11	14.64	13.96	16.86	16.45
1000 / 1033	8.34	7.91	8.91	8.55	9.34	9.00	10.07	9.70	11.10	10.86	13.42	13.49
1500 / 1550	7.20	6.93	7.72	7.51	8.34	8.21	8.68	8.58	9.87	9.84	12.65	12.70
2500 / 2583	6.80	6.56	7.54	7.36	7.92	7.78	8.49	8.34	9.64	9.52	12.29	12.28

Source: Reference 24 (1968).

Plant Type
- I-A Cooling tower and steam generation equipment.
- I-B Steam generation equipment but no tower.
- II-A Cooling tower no steam generation equipment.
- II-B No cooling tower, no steam generation equipment.

The determination of the price that a manufacturer could afford to pay for pyrite-coal reject material was approached in two ways. The first involves a comparison total manufacturing cost for making 98% acid from elemental sulfur versus the cost for making it from pyrite, assuming both raw materials are delivered at the plant site. To do this, a functional relation was established expressing acid manufacturing costs as a function of price of elemental sulfur f.o.b. the acid plant, assuming plants of various capacities and 15 percent return on investment. Acid manufacturing costs were determined for various prices of sulfur. A second functional relation was developed expressing acid manufacturing costs for the same type and size of plant and return on investment as a function of delivered price of pyrite feedstock of various grades. The prices that could be paid for pyrite to maintain acid manufacturing costs equal to the costs corresponding to various prices of sulfur was thereby determined. Results are presented in Table XXXVII.

The second approach to determining pyrite prices considered the case where pyrite would be used to manufacture acid as part of an integrated operation to produce high analysis fertilizer (diammonium phosphate). A brief analysis of the supply and demand for this type of fertilizer revealed a high demand in the upper midwestern U.S. Production within the region meets only about half of the demand, the remainder being supplied primarily by production in the southeastern and Gulf states.

Studies of the logistics of transporting pyrite rejects from coal producing areas to an integrated fertilizer plant and transporting fertilizer from the plant to upper midwestern market areas indicated that the

TABLE XXXVII
THE PRICE THAT CAN BE PAID FOR PYRITES TO YIELD THE SAME SULFURIC ACID MANUFACTURING COST AS WHEN USING BRIMSTONE AT VARIOUS PRICES

Acid Plant Capacity (Short Tons Per Day)	Pyrites Feed[2] Composition	Delivered Pyrites Price ($ Per Short Ton) When the Delivered Price of Brimston per Long Ton is: $35	$40	$45
500	4	1.49	3.52	5.54
1000	4	4.00	6.03	8.05
1500	4	5.24	7.26	9.29
2500	4	5.50	7.52	9.55
500	6	0.46	2.48	4.51
1000	6	3.37	5.54	7.70
1500	6	4.48	6.65	8.81
2500	6	5.10	7.26	9.44
500	8	-0.46	1.57	3.49
1000	8	1.71	3.48	5.26
1500	8	3.12	4.89	6.67
2500	8	3.36	5.14	6.91

Source: Reference 24 (1968).

Feed Composition			
Number	% Pyrite	% Coal	% Gangue
4	80	7	13
6	85	10	5
8	70	10	20

preferred location of such a plant would be the Cairo, Illinois - Paducah, Kentucky area. Cost studies to determine pyrite prices were based on a plant in this location.

The plant using pyrite as a source of sulfur was assumed to compete with another diammonium phosphate fertilizer plant which could be in either of two locations. In one case, the competing plant would be located in Cairo, and would use elemental sulfur shipped in from the Gulf coast. In the other case the competing plant would be in Baton Rouge, Louisiana, a location considered typical of new phosphate plants under construction at the time of this study. It would use Gulf coast sulfur and its product fertilizer would be shipped to Cairo. Functional relations for these two cases (Case A and Case B respectively) are shown in Figure 37, which indicates that the more severe competition would be imposed by the Baton Rouge-based plant. The data in the figure are based on a 10 percent return on fixed investment. It is realistic to assume that fertilizer production in the Gulf coast area will, in fact, provide the competition indicated in this example. From the Case A (Baton Rouge) curve, one sees that when sulfur sells for $38 per ton f.o.b. mine, the fertilizer manufacturer could afford to pay $1 per ton for 85 percent pyrite delivered to his plant and remain competitive. If the sulfur price rose to $48/ton, he could pay about $3.50/ton for pyrite, but if it fell below $33 the price he could pay for pyrite becomes negative, and the Cairo manufacturer could not successfully compete, with regard to the acid-making step in his total operation.

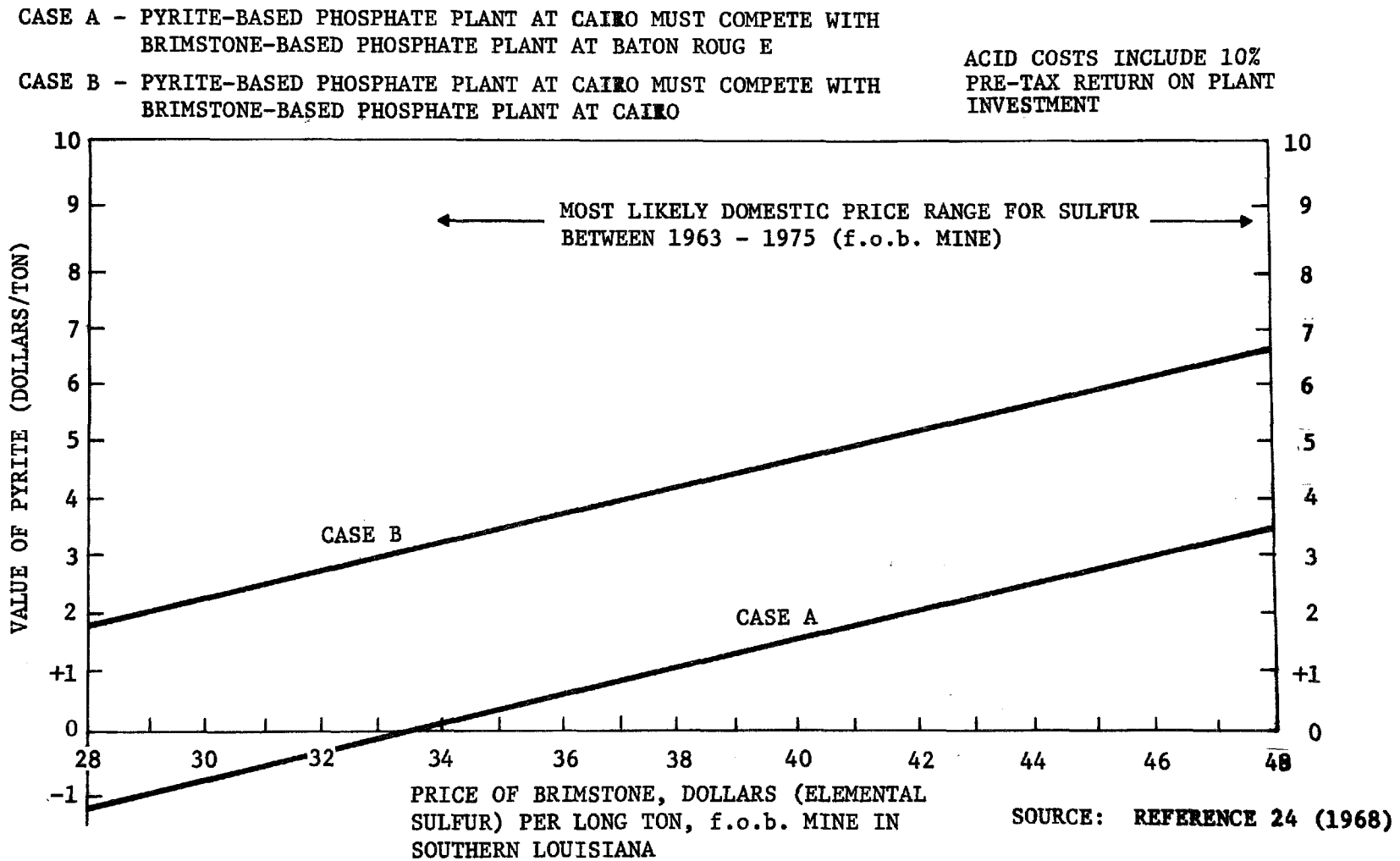


FIGURE 37

ESTIMATED VALUE OF PYRITE FOR SUPPLYING SULFURIC ACID TO PHOSPHATE FERTILIZER PLANT AT CAIRO, ILLINOIS AS A FUNCTION OF–

1. Prevailing Price of Brimstone (Elemental Sulfur)
2. Location of Brimstone–Based Phosphate Plant–Baton Rouge, La., or Cairo, Ill.

A different set of functional relations similar to those of Figure 37 would apply if different rates of return on investment were applied to the plant using pyrite feed. Table XXXVIII shows the effects of this parameter on allowable price for pyrite, when the return on investment for the competing plants utilizing brimstone is held at 10 percent.

It should be emphasized that the pyrite prices cited above and in Table XXXVIII are as delivered to the acid production plant. When the cost of transportation from the coal preparation plant to the acid (or fertilizer) plant is considered, the above prices must be adjusted by deducting transportation costs. If it is assumed that the cost of transportation of pyrite reject from a preparation plant in western Kentucky or southern Illinois is 50 cents per ton, then the acid manufacturer could afford to pay the prices tabulated in Table XXXVIII, less 50 cents, for pyrite at the preparation plant. If the pyrite source is the northern Appalachian coal producing region, then the transportation costs are grossly estimated as 50 cents per ton from preparation plant to dockside in Pittsburgh, Pennsylvania, plus $2.00 per ton by barge from Pittsburgh to Cairo, Illinois. Thus, the prices in Table XXXVIII must be reduced by $2.50 per ton to arrive at the estimated price allowable for pyrite reject f.o.b. at a preparation plant in the northern Appalachian region.

7.5 Findings

The following conclusions may be drawn from the studies performed by Bechtel Corporation and Arthur D. Little, Inc., on process costs and economics of pyrite coal utilization:

TABLE XXXVIII

ALLOWABLE PRICES FOR 85 PERCENT PYRITE DELIVERED TO CAIRO PLANT

UNDER VARIOUS RETURN-ON-INVESTMENT REQUIREMENTS*

($ Per Ton)

INVESTMENT CONDITION	COMPETING WITH PLANTS USING ELEMENTAL SULFUR AT	
	Baton Rouge, La.	Cairo, Ill.
Straight Manufacturing Costs with No Cost For Capital Included	2.42	5.65
10% Return on Fixed Investment (ROI) for both Pyrite-Fed Plants and Sulfur-Fed Plants	1.00	4.23
15% ROI for Pyrite-Fed Plants and 10% ROI for Sulfur-Fed Plants	(0.14)	3.09
20% ROI for Pyrite-Fed Plant and 10% ROI for Sulfur-Fed Plant	(01.28)	1.95

*Assume: Price of Elemental Sulfur is $38 per ton f.o.b. Mine

Source: Reference 24 (1968).

- The reject material from large coal preparation plants that process pyrite-bearing coal contains sufficient quantities of sulfur, sulfur compounds, and coal (in addition to ash) to permit recovery of energy of sulfur values on a commercial scale.
- Adequate technology exists, in the form of several commercially-used and proven processes, for recovery of sulfur values of pyrite materials as elemental sulfur or sulfuric acid and energy values as steam or electric power. These processes have been applied to mined pyrites but have not yet been applied to utilizing the pyrite-bearing refuse from coal preparation plants as feedstock.
- Preliminary studies indicate that several processes are technically capable of accepting such refuse as feedstock, although certain of the processes require preliminary concentration of the refuse to increase its pyrite content.
- All processes considered require some degree of modification to accommodate the relatively low-pyrite, high-ash feedstock. One reason is the low concentration of sulfur dioxide in the combustion gases generated by burning reject material rather than elemental sulfur or pyrites. By enriching the input air with pure oxygen, a higher concentration of sulfur dioxide in the combustion products may be obtained, thereby minimizing the required modifications to existing equipment and process design.

- There is a large and relatively stable market for sulfuric acid. The competitive status of processes for converting the sulfur content of coal preparation plant refuse to sulfuric acid (for other salable products), compared with processes using elemental sulfur as a feedstock, is highly dependent on the availability and market value of elemental sulfur, which fluctuates greatly as some sources are exhausted and others are discovered.
- Under conditions of the sulfur market at the time of the referenced studies, two specific processes for recovering sulfur value and electric power from coal preparation refuse were found to be economically viable: the refuse-combustion/sulfur-oxides-removal process (which accepts the entire refuse stream) and the fluid-bed roasting process (which require preliminary concentration of the refuse).
- The use of oxygen to enrich the input combustion air would be advantageous in permitting higher utilization of conventional process equipment, but would not be economically advantageous because of oxygen costs and certain technical considerations relating to heat transfer.

8.0 THE HIGH SULFUR COMBUSTOR -- A STUDY OF SYSTEMS FOR UTILIZATION OF COAL CLEANING REJECT MATERIAL

8.1 Objectives and Approach

A study was performed by the Chemical Construction Company (Chemico) during 1970 and 1971 to identify a combustor system for utilizing reject material produced by the physical desulfurization of coal and to integrate the combustor into a system for recovering the energy and sulfur values of the reject material. Emphasis was on equipment selection and design. Specific tasks of the study were:

- To select/design an appropriate combustor;
- To select/design processes for recovery of sulfur values as sulfur or sulfuric acid, with emphasis on those processes in commercial use (or nearly so);
- To determine properties of reject material that influence combustor design;
- To establish procedures to characterize reject material for use as fuel;
- To establish specifications for reject material for use as a fuel;
- To perform a conceptual design of a prototype plant;
- To estimate costs of plant and of the overall operation, including coal cleaning;
- To extrapolate design to full-scale industrial and utility plants with energy outputs in the range from 500,000 lb/hr of

industrial-quality steam to 500 megawatts electrical power, with each design providing for recovery of sulfur values;

- To coordinate this study with other elements of EPA's Clean Coal Program.

These tasks were approached by first examining the characteristics of raw coal in the geographic area of interest and capabilities of various methods of physical desulfurization. This made it possible to define the ranges of reject characteristics for which recovery systems would be designed, the characteristic of major interest being the sulfur-to-carbon ratio (S/C ratio) in the reject material.

Next, five "case studies" were developed consisting of very general performance specifications of various types of plants to extract both energy and sulfur values from rejects having sulfur-to-carbon ratios across the range of interest. Conceptual plant designs were developed for the five case studies and estimates of capital and operating costs were developed for each design. More detailed engineering designs, equipment specifications, and cost estimates were prepared for a prototype demonstration plant fitting one of the case studies.

The study concludes that the reject material produced by the removal of iron pyrites and ash from coal by conventional coal cleaning operations can be blended to form a high sulfur fuel suitable for firing an appropriately designed plant to generate electric power and recover sulfur values. The prototype plant design developed in the study would provide the capability to demonstrate technical feasibility on a reduced

scale (output: 50 megawatts electric and 100 tons/day sulfur) and to further investigate the economics of such an operation, which appears economically viable in preliminary analysis of a larger-scale plant (output: 500 megawatts electric and 770 tons/day sulfur).

The 50 megawatt plant design selected for more detailed analysis and possible implementation as a prototype plant employs the same basic power generating system and technically-advanced sulfur recovery process as the 500 megawatt plant. Although not of commercial scale, it is of sufficient size to permit investigation of the effects of variations in fuel characteristics and operating conditions on power and sulfur output and to produce good estimates of operating costs. However, it is not so large that disposal of sulfur and waste products is likely to present a major problem. The production of sulfur in its elemental form helps to separate the basic problem of sulfur recovery coupled with power generation from the more complex problem of conversion to sulfuric acid. Also, since elemental sulfur is easy to store and costs less to ship than sulfuric acid, the location of a prototype plant producing elemental sulfur would be less critical, in terms of proximity to acid-consuming industry, than a plant producing sulfuric acid.

8.2 Types of Coal and Effects of Coal Cleaning

A review of the effects of various methods of physically cleaning and desulfurizing coals produced in the six-state area of interest (Pennsylvania, Ohio, West Virginia, Kentucky, Indiana and Illinois) led to the following conclusion relating directly to the design of combustor systems:

> If, by size reduction and separation, it is feasible to separate fractions to recover coal low in pyritic sulfur content and to recover pyritic fractions low in coal content, then, by recombining these fractions, it is possible to produce high-sulfur fuel having a controlled ratio of pyritic sulfur to coal. The characteristics of such fuels can thus be tailored to the requirements of specific combustion-systems designed for the economic recovery of energy and sulfur values.

For the five case studies Foster-Wheeler did considerable work on determining feed compositions which were suitable. Bituminous Coal Research, Inc., (BCR) demonstrated that the compositions specified by Foster-Wheeler could be produced through such means as blending, etc. BCR also performed work on the utilization of clean coal fractions. Thus, the assumption is made that almost any run-of-mine coal containint pyrites can, in general, be processed to yield low sulfur coal plus a high-sulfur fuel.

This conclusion permits establishing ranges of interest for the parameters characterizing high sulfur fuels, and selecting fuels having specific characteristics, upon which plant design can be based.

8.3 High Sulfur Fuel Characteristics

Reject material from coal cleaned to reduce sulfur content ordinarily contains higher percentages of pyrites and non-pyritic ash and a lower percentage of carbon than run-of-mine coal. The sulfur content may range from a minimum of about one percent (assuming this one percent to be the nominal maximum for "desulfurized" coal) to a theoretical maximum of about 58 percent (corresponding to pure pyrite).

The combustion in air of a known mixture of sulfur and carbon results in predictable sulfur dioxide concentration in the combustion gas.

For practical purposes this is also true of known sulfur-coal and iron-pyrite mixtures when the conposition of the coal is also known. Sulfur dioxide concentrations expected from combustion of sulfur-carbon mixtures can be plotted according to S/C ratios. The use of the S/C ratio for this purpose avoids the ambiguity of "percent sulfur in coal" which is determinant of total sulfur but not of flue gas composition. However, coal is not pure carbon and use of the S/C ratio results in some minor inconsistencies. The S/C ratio of high sulfur combustor (HSC) fuel must be held to narrow limits to stabilize the heating value of the fuel and to avoid penalizing the sulfur recovery operation.

The iron-pyritic ash content must also be controlled, partially to maintain a specific heating value, but more importantly to avoid an unpredictable ash fusion temperature. Failure to control ash content can adversely affect the yield of cleaning operations and the capability of the furnace designed to burn the HSC fuel.

For recovery of sulfur values from the reject, the percent sulfur in the fuel is not of as much concern as the ratio of sulfur to carbon. This sulfur-to-carbon ratio bears an almost direct relation to the percentage of sulfur dioxide in the gaseous products of combustion, from which the sulfur must be recovered. In general, higher concentrations of sulfur dioxide promote efficiency of recovery, at least in currently available technology. The percentage of sulfur dioxide may range from a small fraction of a percent from burning a relatively clean fuel (say one or two percent sulfur) to about 13 percent from burning pure pyrite

(58 percent sulfur). However, high sulfur fuels made from reject materials will not fall near the high or low end of the scale for either percent sulfur or sulfur-to-carbon ratio, but within the mid-range.

The following limits were selected to define the range of interest for high-sulfur fuel composition:

Parameter	HSC FUEL*[25] Lower Limit	Upper Limit
Sulfur-to-carbon ratio	.08	2
Percent S in fuel, (approximate)	7	42
Equivalent percent pyrite in fuel, (approximate)	13	79
Percent coal combustible (sulfur-free) in fuel, approximate)	87	21
Higher heating value of fuel, (approximate)	12600	5300

Although fuels of various compositions falling within this range were selected for the various case-study process designs, the basic approach is to design the process to fit the market, and to tailor-make the fuel to suit the process.

8.4 Performance Requirements for Recovery Systems--Base Parameters for Five Case Studies

Three process systems utilizing currently available technology appear capable of fully exploiting the full range of opportunities for recovering energy and sulfur values from high-sulfur coal-pyrites. The chemical processes selected for recovery of sulfur values or the standard contact process, the Monsanto Cat-Ox process, and the magnesium sulfite/

oxide process. Five case studies involving these systems were defined as follows (letter designations are arranged to group similar processes instead of in alphabetical order):*

CASE A: Energy Product: 500,000 lb/hour industrial steam

Sulfur Product: 1800 tons/day 100% sulfuric acid

Fuel S/C Ratio: 2.0

CASE A is designed for firing a high sulfur fuel having a sulfur-to-carbon ratio of about 2 to produce 500,000 lbs/hr of industrial quality steam and a flue gas of 6 percent SO_2 concentration which is directly converted to some 1,800 tons/day of commercial grade sulfuric acid. These outputs would be secondary coproducts of clean coal produced at a rate of 7 million tons per year by washing a run-of-mine coal containing 3 percent pyritic sulfur. The actual clean coal output would, of course, depend on the actual run-of-mine composition and washability.

A system of this type is conceived to be of possible value as an addition to an existing coal-burning utility complex, or existing chemical or steelmaking industry.

CASE B: Energy Product: 500,000 lb/hour industrial steam

Sulfur Product: 77% sulfuric acid equivalent to 624 tons/day (100% basis)

Fuel S/C Ratio: 0.4

*Adapted from Reference 25 (1971)

CASE B is designed to use the Monsanto Cat-Ox process for recovery of sulfur as 77-80 percent sulfuric acid. Since a lower sulfur-carbon ratio fuel is used, a smaller quantity of acid would be produced, the steam output rate remaining constant.

CASE E:	Energy Product:	500 megawatts electric power
	Sulfur Product:	77% sulfuric acid, equivalent 1420 tons/day (100% basis)
	Fuel S/C Ratio:	0.12

CASE E employs an SO_2 recovery technology (Monsanto Cat-Ox) similar to CASE B but this system is scaled to the 500 MW output level (more than 10 times the energy capacity of CASE B) so that the combustion equipment is quite different. The SO_2 recovery trains operate on relatively weak gas of 0.7 percent SO_2 which is generated by a sulfur/carbon ratio of 0.12.

CASE D:	Energy Product:	500 megawatts electric
	Sulfur Product:	770 tons/day elemental sulfur
	Fuel S/C Ratio:	0.2

CASE D is also scaled to 500 MW energy output but the SO_2 recovery technology is quite versatile compared to processes mentioned above. The acid intermediates—liquid SO_2, magnesium sulfite, or

sulfur--can be produced for storage or shipment, or sulfur value can be converted directly to sulfuric acid, any of these by available technology. The main design theme of CASE D in this study is for output of sulfur at 770 net tons per day from a 1 percent SO_2 flue gas that requires a sulfur/carbon ratio of 0.2

CASE C:	Energy Product:	50 megawatts electric
	Sulfur Product:	102 tons/day elemental sulfur
	Fuel S/C Ratio:	0.2

CASE C is the reduced-scale prototype or demonstration unit of CASE D, designed to operate on the same HSC fuel composition but at 50 MW energy capacity and about 100 tons per day of sulfur.

These cases cover sulfur-to-carbon ratios from 0.12 to 2.0. Cases A and B are primarily of industrial interest, Cases D and E are of utility interest with chemical co-products, and Case C is for demonstration. The plant design for Case C was carried to much greater detail than for the other case studies.

8.5 Selection of Equipment and Fuel Compositions

8.5.1 High Sulfur Fuels

Reject materials produced by coal cleaning operations were reviewed with respect to sulfur content, coal content, non-pyritic ash content, heat value, and other relevant characteristics. Fuel compositions for each case study were specified, based on the following ground rules:

- High sulfur fuel specifications must be compatible with optimum total yield of fuel value from the coal cleaning plant.
- Sulfur/carbon ratio must be controlled within narrow limits to facilitate recovery operations.
- Non-pyritic ash content must be controlled to avoid unpredictable ash fusion temperature.

Fuels for each case study were specified in terms of proximate and ultimate analyses. These will be presented in abbreviated form in later exhibits describing the processes employed in each case study (see Section 8.5.6).

Test procedures recommended for defining, preparing, and controlling the quality of high sulfur fuels were:

- Ultimate Analysis;
- Proximate Analysis;
- Heating Value;
- Hardgrove Grindability;
- Reactivity (Ignition Index);
- Chemical Analysis of Ash;
- Ash Fusion, Reducing and Oxidizing Atmosphere;
- Size Analysis;
- Free Swelling Index.

Only one of the nine tests, reactivity, is not commonly accepted in common practice. It was included because it appears to be the best

indicator of combustion conditions over a wide range of fuel specifications.[25]

8.5.2 Furnace Types

The following types of furnace were considered:

1. Roasting Equipment
   - (a) Kiln
   - (b) Multiple Hearth
   - (c) Flash Roasters
2. Fluidized Bed Combustors
3. Stoker Furnaces
4. Grate Furnaces
5. Crushed Coal-Fired
   - (a) Cyclone Furnace
6. Pulverized-Fuel Fired
   - (a) Wet bottom furnace
   - (b) Dry bottom furnace
     - Horizontally fired
     - Vertically fired.

Types 1, 3, and 4 were eliminated from consideration because they cannot be fired at sufficiently high temperatures to meet steam production requirements.[25] Type 2 (fluidized bed) was dropped because it is not established commercially for this type of operation and because of the uncertain behavior of a coal-pyrite-ash mixture in a fluidized bed

containing tubes. Type 5(a) (Cyclone) was eliminated because of high maintenance costs which could be aggravated by a high-iron, high sulfur fuel.

Pulverized-fuel fired systems were considered preferable to suspension-fired ones on the basis of fuel characteristics, thus eliminating Type 4 (grate). Wet bottom furnaces (Type 6(a)) were considered unsuitable because of the high ash fusion temperatures resulting from high iron content.

Thus, by elimination, the dry-bottom, pulverized-fuel-fired type of furnace was considered to be relatively risk-free, reliable, and most generally suitable for all cases studied.

8.5.3 Boilers, Burners, and Combustion Systems

Specific types of combustion systems were selected for Cases A, C, and D. Combustor designs for Case B were not developed since funds were not provided, but cost estimates for Case B equipment were made on the basis of a modified Case A design. The Case D combustor system is suitable for Case E with minor modifications.

For Case A, an individual-type boiler fired by a special burner firing vertically downward, was selected to produce 500,000 lb/hour of steam at a pressure of 900 psig.

For Case C, which requires a rate of steam production similar to Case A but at a higher pressure for generating electric power, a utility-type boiler fired horizontally with an intervane burner was selected to produce some 500,000 lb/hour of steam at 1450 psig.

For Case D, a utility-type boiler was selected to produce larger quantities of higher quality steam which are fed to 500 MW turbo-generators. As in Case C, a larger utility boiler fired horizontally with intervane burners was selected. It would produce some 3.5 million lb/hour of steam at 2500 psig.

The Case E equipment would be a modification of the Case D equipment.

8.5.4 Electric Generating Equipment

Electric generators driven by a conventional turbine drive cycle were selected for both the 50 MW requirement (Case A) and the 500 MW requirement (Cases D and E).

The 500 MW size was fairly typical of U.S. utility installations *ca*. 1960. More recently this capacity (i.e., 500 MW) has been toward the lower end of the range, with most installations falling between 600 and 850 MW. Capacities around 50 MW are still in use for some municipalities, industrial installations, etc. Generating equipment of much lower capacities is often considered as "special order" with much higher cost per unit output. Hence the 50 MW size appeared about right for a prototype demonstration plant.

8.5.5 Processes for Recovery of Sulfur Values

Sulfur values can be recovered from the gaseous products of pyrite combustion in several forms, including sulfuric acid, elemental sulfur, sulfur dioxide (liquid), and metallic sulfites. Sulfuric acid is usually the salable end-product, and the other forms of recovered sulfur

may be considered intermediate materials for the production of acid. As discussed in Section 7, there are advantages to shipping sulfur in forms other than sulfuric acid because of the acid's high specific gravity. Hence, under some logistic situations, one of the intermediate forms of sulfur may be the more desirable output of a recovery operation.

The following processes for producing sulfuric acid or acid intermediates were considered for use in the plant designs for the various case studies:

- Processes Yielding Sulfuric Acid:
  - the "Standard" contact process;
  - the Monsanto Cat-Ox process (a modification of the basic contact process permitting use of sulfur dioxide concentrations in the range of 2 percent down to a few tenths of a percent);
  - the Lurgi process;
  - the Hitachi process;
- Processes for Concentrating Gas Mixtures Low in Sulfur Dioxide to Intermediate Levels:
  - the Reinluft process (using char absorption);
  - the Grillo process (using metallic oxide absorption);
  - the Magnesium Sulfite/Oxide process;
- Processes for Concentrating Weak Sulfur Dioxide Mixtures to High Levels (90-100 percent):

- aromatic amine absorption;
- basic aluminum sulfate absorption;
- thermal cycle absorption (using water as solvent);
- alkali-metal sulfite/bisulfite absorption (Wellman-Lord process);

- Processes Yielding Elementary Sulfur:
  - reduction of high-concentration sulfur dioxide by hot coke;
  - reduction of dilute sulfur dioxide by produce gas (a mixture of hydrogen and carbon monoxide);
  - reduction of dilute sulfur dioxide by reformed natural gas (methane);
  - reduction of sulfur dioxide by methane (non-catalytic);
  - reduction of sulfur dioxide by methane (the West process);
  - reduction of sulfur dioxide by hydrogen sulfide (the Claus process).

Three processes (or combinations) from among the above were selected as adequate to exploit the full range of potentials for sulfur value recovery presented by the five case studies. These were employed as follows:

Case A -- "Standard" Contact Process;

Case B -- Monsanto Cat-Ox Process;

Case C -- Magnesium Sulfite/Oxide Process;

Case D -- Magnesium Sulfite/Oxide Process;

Case E -- Monsanto Cat-Ox Process.

8.5.6 Process Description and Fuel Composition for Each Case Study

Summary descriptions of the processes, fuels, and products for each case study are presented in Tables XXXIX, XL, XLI, XLII, and XLIII. Process flow charts for each case study can be found in Reference 25, Part VII; additional design detail is presented in Parts XIII through XVII of this reference. The Case C prototype plant design is accorded special attention in Part XV.

To facilitate comparison among the five case studies, the fuel input requirements and outputs of each are summarized in Table XLIV. This table shows the quantities of clean coal produced and the quantity of high sulfur fuel derived from the coal-cleaning reject material. It also shows the resulting energy value and sulfur value obtained from utilizing the high sulfur fuel. Equivalent quantities of sulfur products for each case study are shown for purposes of comparison; however, the equipment specified in certain of the case studies is not adapted to produce all of the sulfur products shown in this Table. Comparison of the relative quantities of the various forms of sulfur products suggest that when the product is to be shipped over considerable distances or when storage space is at a premium it may be highly advantageous to produce the sulfur in elemental form, or as another sulfur compound, instead of sulfuric acid.

8.6 Economic Analyses of the Five System Designs

Capital costs and annual operating costs (less cost of high sulfur fuels) for the processing system employed in each case study were

TABLE XXXIX
SUMMARY OF CASE A

PRODUCTS

Energy Product: 500,000 lb/hour at 825°F

Sulfur Product: 98% sulfuric acid, equivalent to 1830 tons/day (100% basis)

SUMMARY

A run of mine bituminous coal containing 3 to 4.5% sulfur, washable to 1% sulfur, is assumed. The reject is treated for maximum yield of a high-sulfur fuel of the CASE A specification. This fuel is pulverized and fired to raise 500,000 lbs/hr of industrial quality steam and a flue gas containing 6% sulfur dioxide and 4.3% oxygen. The gas is wet cleaned in a packed tower, dried and converted catalytically to sulfur trioxide which is reacted with water to make 98% sulfuric acid at the rate of 1,830 net tons (100% basis) per day, 330 days per year. Sulfur emission equals 0.4% of sulfur charged. Sulfur not emitted equals 93 pounds per million Btu of heat recovered in the CASE A System, or 2.2 pounds per million Btu of ROM coal charged to the cleaning plant.

FUEL CHARACTERISTICS

Constituents (Wt. % Dry Basis*)	Run of Mine Coal	Clean Coal	High-Sulfur Fuel
Iron Pyrite		1.0	61.6
Organic Sulfur		1.0	0.2
Total Sulfur	3 to 4.5		(33.1)
Coal Combustibles			18.2
Non-Pyritic Ash			20.0
M Tons/Year			640.0
Tons/Hr: Iron Pyrite			49.3
Coal Combustibles			14.7
Non-Pyritic Ash			16.0
Sulfur/Coal Ratio			1.8
BTU/LB			4420
BTU/HR			700×10^6

* 6% Moisture assumed in high sulfur fuel as fired

Source: Adpated from Reference 25 (1971).

TABLE XL
SUMMARY OF CASE B

PRODUCTS

Energy Product:	500,000 lb/hour at 825°F
Sulfur Product:	77% sulfuric acid equivalent to 624 tons/day (100% basis)

SUMMARY

A run of mine bituminous coal containing 3 to 4.5% sulfur, washable to 1% sulfur, is assumed. The reject is treated for maximum yield of a high sulfur fuel of the CASE B specification. This fuel is pulverized and fired to raise 500,000 lbs/hour of industrial quality steam and a flue gas containing 2% sulfur dioxide and 4.2% oxygen. The gas is cleaned of particulates in an electric precipitator at 805° F and is then converted catalytically to sulfur trioxide which is reacted with water to make 77%-80% sulfuric acid by the Cat-Ox process of Monsanto at the rate of 624 net tons (100% basis) per day, 330 days per year. Sulfur emission equals 0.5% of sulfur charged. Sulfur not emitted equals 33 pounds per million Btu of heat recovered in the CASE B System, or 2.0 pounds per million Btu of ROM coal charged to the cleaning plant.

FUEL CHARACTERISTICS

Constituents (Wt. % Dry Basis*)	Run of Mine Coal	Clean Coal	High-Sulfur Fuel
Iron Pyrite			33.8
Organic Sulfur			0.5
Total Sulfur	3 to 4.5		(18.5)
Coal Combustibles			45.7
Non-Pyritic Ash			20.0
M Tons/Year			406
Tons/Hr: Iron Pyrite			17.1
Coal Combustibles			23.4
Non-Pyritic Ash			10.1
Sulfur/Coal Ratio			0.4
BTU/LB			7400
BTU/HR			750×10^6

* 6% Moisture assumed in high sulfur fuel as fired

Source: Adapted from Reference 25 (1971).

TABLE XLI
SUMMARY OF CASE C

PRODUCTS

Energy Product: 50 megawatts electric at 500° F

Sulfur Product: 102 tons/day elemental sulfur

SUMMARY

A run of mine bituminous coal containing 3 to 4.5% sulfur, washable to 1% sulfur, is assumed. The reject is treated for maximum yield of a high sulfur fuel of the CASE C and D specification. This fuel is pulverized and fired to raise 500,000 lbs/hr of sub-critical steam which is fed to a turbo-generator of 50 MW capacity. The flue gas containing about 1% sulfur dioxide and 4.3% oxygen is wet-cleaned in a venturi scrubber and led to a two-stage-venturi absorber in which sulfur dioxide is reacted, essentially with magnesium oxide, to produce magnesium sulfite. This salt is separated, dried, and calcined to yield a 15% sulfur dioxide gas concentrate and magnesium oxide which is recycled. The 15% sulfur dioxide is converted by catalytic reduction to sulfur at the rate of about 100 net tons per day, 330 days per year. Sulfur emission equals 1.3% of sulfur charged. Sulfur not emitted equals 16 pounds per million Btu of heat recovered in the CASE C Prototype System, or 2.2 pounds per million Btu of ROM coal charged to the cleaning plant.

FUEL CHARACTERISTICS

Constituents (Wt. % Dry Basis*)	Run of Mine Coal	Clean Coal	High-Sulfur Fuel
Iron Pyrite			20.8
Organic Sulfur		1.0	0.6
Total Sulfur	3 to 4.5		(11.7)
Coal Combustibles			58.6
Non-Pyritic Ash			20.0
M Tons/Year			298.0
Tons/Hr: Iron Pyrite			7.7
Coal Combustibles			22.0
Non-Pyritic Ash			7.4
Sulfur/Coal Ratio			0.2
BTU/LB			9000
BTU/HR			670×10^6

* 6% Moisture assumed in high sulfur fuel as fired

Source: Adapted from Reference 25 (1971).

TABLE XLII
SUMMARY OF CASE D

PRODUCTS

Energy Product: 500 megawatts electric at 500° F

Sulfur Product: 770 tons/day elemental sulfur

SUMMARY

A run of mine bituminous coal containing 3 to 4.5% sulfur, washable to 1% sulfur, is assumed. The reject is treated for maximum yield of a high sulfur fuel of the CASE C and D specification. The fuel is pulverized and fired to raise 3.5 million pounds per hour of subcritical steam which is fed to a turbo-generator of 500 MW capacity. The flue gas composition is identical to that of CASE C and is treated in an identical manner to yield 770 net tons per day of sulfur. Sulfur emission equals 0.8% of sulfur charged. Sulfur not emitted equals 16 pounds per million Btu of heat recovered in the CASE D System, or 2.3 pounds per million Btu of ROM coal charged to the cleaning plant.

FUEL CHARACTERISTICS

Constituents (Wt. % Dry Basis*)	Run of Mine Coal	Clean Coal	High-Sulfur Fuel
Iron Pyrite			20.8
Organic Sulfur			0.6
Total Sulfur	3 to 4.5		(11.7)
Coal Combustibles			58.6
Non-Pyritic Ash			20.0
M Tons/Year			2280
Tons/Hr: Iron Pyrite			59.3
Coal Combustibles			338.0
Non-Pyritic Ash			57.0
Sulfur/Coal Ratio			0.2
BTU/LB			9000
BTU/HR			$5,128 \times 10^6$

* 6% Moisture assumed in high sulfur fuel as fired

Source: Adapted from Reference 25 (1971).

TABLE XLIII
SUMMARY OF CASE E

PRODUCTS

Energy Product:	500 megawatts electric power at 850° F
Sulfur Product:	77% sulfuric acid, equivalent to 1420 tons/day (100% basis)

SUMMARY

A run of mine bituminous coal containing 3 to 4.5% sulfur, washable to 1% sulfur, is assumed. The reject is treated for maximum yield of a high sulfur fuel of the CASE E specification. This fuel is pulverized and fired to raise 3.5 million pounds per hour of sub-critical steam which is fed to a turbo-generator of 500 MW capacity. The flue gas containing 0.7% sulfur dioxide and 4.2% oxygen is treated by the Monsanto Cat-Ox process in a manner similar to CASE B, but in multiple trains, to yield 1,420 net tons (100% basis) of 77%-80% sulfuric acid per day. Sulfur emission equals 1.5% sulfur charged. Sulfur not emitted equals 10 pounds per million Btu recovered in the CASE E System, or 2.3 pounds per million Btu of ROM coal charged to the cleaning plant.

FUEL CHARACTERISTICS

Constituents (Wt. % Dry Basis*)	Run of Mine Coal	Clean Coal	High-Sulfur Fuel
Iron Pyrite			13.2
Organic Sulfur			0.9
Total Sulfur	3 to 4.5		(7.9)
Coal Combustibles			65.9
Non-Pyritic Ash			20.0
M Tons/Year			2133
Tons/Hr: Iron Pyrite			35.2
Coal Combustibles			178.0
Non-Pyritic Ash			53.3
Sulfur/Coal Ratio			0.12
BTU/LB			9660
BTU/HR			5150×10^6

* 6% Moisture assumed in high sulfur fuel as fired

Source: Adpated from Reference 25 (1971).

TABLE XLIV
SUMMARY OF INPUTS AND OUTPUTS FOR FIVE CASE STUDIES

Case	Input (Million Tons/Yr.)	Output of Coal Processing Operation (Million Tons/Yr.)		Output of Power and Sulfur Recovery Operations					
				Energy		Sulfur Values (Net Tons/Day, Approx.)			
	Run-of-Mine Coal	Clean Coal	High-Sulfur Fuel	Electrical (Megawatts)	Steam (Lb./Hour at 825 F)	Elemental Sulfur	Sulfuric Acid Equivalent	Magnesium Sulfate Equivalent	Liquid Sulfur Dioxide Equivalent
D	9.7	7.1	2.3	500		770*	2300	2500	1520
A	8.1	7.1	0.6		500,000	640	1830*	1980	1220
E	5.8	3.5	2.1	500		510	1420*	1580	970
B	2.8	2.3	0.4		500,000	230	624*	710	440
C	1.3	0.9	0.3	50		102*	291	310	190

Notes: (1) ROM: 1% organic S, 3% pyritic S, 13% non-pyritic ash.
(2) Clean Coal: 1% organic S, 5% non-pyritic ash
(3) Clean Coal + HSC fuel = 95% of ROM weight (dry basis)
(4) Total cleaning losses = 5%

* Design Basis for this Case Study

Source: Adapted from Reference 25 (1971).

determined. Anticipated income from sale of products was then estimated, and the allowable cost of high sulfur fuels was determined by difference.

8.6.1 Method for Valuation of High-Sulfur Fuels

The various systems used to recover energy and sulfur values from coal-pyrites may be considered salvage systems to improve the economics of coal cleaning. Sales income, less all costs for energy and sulfur value recovery and other expense, is a basis for valuation of high sulfur fuels. The value of the high sulfur fuel is determined as follows:

High Sulfur Fuel Value = Sales Value of Products (Electric power, sulfuric acid, etc)

less:
- Selling and Commercial Expense
- Extraction Costs
- General Expense and Income Tax
- High-sulfur Fuel Preparation, Transport and Handling Costs ("Precombustion Costs")

plus: Cost of Dumping Refuse (shown as a "plus" to indicate a credit for avoidance of dumping costs).

The "precombustion cost" term has been estimated to be on the order of 81 cents per ton of high sulfur fuel delivered to the combustor; this would increase for longer shipping distances. The dumping cost has been estimated as lying between $1 and $2 per ton of refuse. (Each of these estimates is highly variable with local conditions (land cost, shipping distances, etc.)). For the present analysis, the assumption is made that it is as cheap to prepare and deliver high sulfur fuel as

it is to handle and dump an equal tonnage of refuse; that is, the pre-combustion costs and dumping costs cancel one another out in the above formula.[25]

8.6.2 Capital Costs

Capital costs are considered to include the costs of construction labor, plant equipment, and material in 1971 or 1972. Cost escalations, estimated as 10 percent/year for electrical equipment and 6 to 8 percent for the chemical plant beyond 1972 are not included in the cost analysis. Estimated capital costs for the five case-study systems are given in Table XLV.

8.6.3 Operating Costs

This category includes all costs for extraction of energy and sulfur values except those for high-sulfur fuel, which will be determined later by difference. In addition to annual costs for utilities, labor and supervision, maintenance, and general plant expense, operating costs also include annualized capital costs to the extent that these are reflected by depreciation and interest.

Operating cost estimates were prepared for each of the five case studies using utilities prevalent in the six-state area of interest (Pennsylvania, Ohio, West Virginia, Kentucky, Indiana, and Illinois) during late 1970. Detailed data for Case C (the 50 MW prototype design) is shown in Table XLVI to illustrate the presentation format. (Data for the other cases not included in this summary report can be found in Reference 25, Part VIII.)

TABLE XLV

ESTIMATED CAPITAL COST

	CASE A $M	CASE B $M	CASE C $M	CASE D $M	CASE E $M
Combustor/Boiler	5,110	4,210	4,310	15,760	11,760
Electric Equipment			11,200	56,200	56,200
Sulfur Recovery	11,300	12,500	10,900	44,000	45,700
Off-Sites	1,550	1,550	2,550	10,100	10,500
Land	250	250	250	1,000	1,000
Fixed Capital	18,210	18,510	29,210	128,060	125,160
Working Capital	130	90	60	460	410
Total Capital	18,340	18,600	29,270	128,520	125,570

Source: Reference 25 (1971).

TABLE XLVI

CASE C SYSTEM ESTIMATED OPERATING COST

	Unit	Unit Value	ELECTRICITY Units Per Year	ELECTRICITY Annual Cost	SULFUR Units Per Year	SULFUR Annual Cost
Production						
Energy	MWH		400,000			
Sulfur Value	L.T.				30,910	
Utilities, etc.						
Electricity	MWH	$7.50	3,360	M$ 25	37,360	M$ 280
Cooling Water	MMgal.	8.00	21,600	173	268	2
Boiler Feed Water	Mgal.	0.60	5	3		
Process Water	Mgal.	0.40			113,000	45
Fuel Gas	MMBtu	0.40			2,100,000	840
Chemicals						81
Waste Disposal	N.T.	2.00	110,000	220	25,400	51
Labor						
Supervision	Manhour	8.00	8,760	70	8,760	70
Operators and Helpers	Manhour	5.50	44,000	242	32,000	176
Maintenance				280		430
Plant General Expense						
Factory Overhead	80% of Direct Labor			194		141
Taxes and Insurance	2.5% of Total Capital			403		329
Total Before Depreciation and Interest				M$1,610		M$2,445
Depreciation						
Guideline Life	11 Years	9.1%				1,174
Guideline Life	28 Years	3.6%		578		
Interest (Average)						
Depreciable Capital		4.5%		723		581
Non-Depreciable Capital		9%		153		126
Cost Before HSC Fuel Charge (Rounded)				M$3,060		M$4,330

Source: Reference 25 (1971).

In these presentations, separate costs are assigned to the production of energy and chemical values. Ground rules used in the initial analysis assign all costs for "pollution control" to the recovery of chemical values rather than apportioning it between the two classes of products. This leads to an apparent low cost of energy production and a high cost of chemical value recovery. An adjustment for this effect is indicated in the following section on Operating Economics.

8.6.4 Operating Economics: Cost of High-Sulfur Fuel

The method for estimating allowable prices for high-sulfur reject material is shown in Tables XLVII and XLVIII. Here, the expected income from selling products of the five case study plants is computed on the basic prices expected to prevail in the six-state area, based on an analysis of price trends. Unit price assumptions are shown in Table XLVII. Values of energy products and chemical products are treated separately.

The various categories of expense--costs of selling, operation, etc.--are then subtracted from the income from sales. The resulting pre-tax income is adjusted for "pollution control" expense, which is required because of a computational ground rule which assigned all pollution control costs to the sulfur recovery portion of the system. Note that this adjustment does not affect the combined income, but merely shifts a part of the expense from one product category to another. It should be noted that the pollution control tariff reflected

TABLE XLVII
INCOME FROM SALES COSTS OF OPERATION AND PRODUCTS
GAIN OR LOSS FROM OPERATION

ANNUAL BASIS

				CASE A		CASE B		CASE C		CASE D		CASE E	
	Unit	Unit Value	Annual Quantity	Steam	Sulfuric Acid	Steam	Sulfuric Acid	Electricity	Sulfur	Electricity	Sulfur	Electricity	Sulfuric Acid
Income From Sales													
Steam	Net Ton	$ 1.30	2,000,000	M$ 2,600		M$2,600							
Electricity	MWH	7.50	400,000					M$30,000					
			4,000,000							M$30,000		M$30,000	
Sulfur	Long Ton	25.0	30,910						M$ 770				
			233,300								M$ 5,830		
Sulfuric Acid (100%)	Net Ton	12.75	610,000		M$7,780								
			208,000				M$2,650						
			473,300										M$ 6,040
Less: Selling & Commercial Expense @ 1% of Sales Value				26		26		30		300		300	
@ 5% of Sales Value					389		132		39		292		302
Operating Cost				2,540	3,820	1,880	3,910	3,060	4,330	12,600	20,630	11,630	14,970
General & Administrative @ 2% of Sales				52	156	52	53	60	15	600	117	600	121
Total Cost Before U.S. Income Tax (Rounded)				M$ 2,620	M$4,370	M$1,960	M$4,100	M$3,150	M$ 4,380	M$13,500	M$21,000	M$12,500	M$15,400
Adjustment for "Pollution Control"				9,380		4,520		2,630		14,450		10,620	
Add					9,380		4,520		2,630		14,450		10,620
Deduct				M$12,000		M$6,480		M$5,780		M$28,000		M$23,100	
Adjusted Cost of Energy Extraction													
Unit Cost of Energy Products:													
Per Net Ton of Steam				$ 6.00		$ 3.20							
Per Megawatt Hour								$ 14.50		$ 7.00		$ 5.80	
Incremental Cost of Sulfur Value Recovery					(M$5,010)		(M$ 420)		M$ 1,750		M$ 6,550		M$ 4,780
Unit Cost of Sulfur Products:													
Per Long Ton of Sulfur									$ 57.00		$ 28.00		
Per Net Ton of Sulfuric Acid					($ 8.20)		(2.00)						$ 10.00
Combined Sales Value of Products				M$10,380		M$ 5,250		M$ 3,770		M$ 35,830		M$ 36,040	
All Costs Before U.S. Income Tax				6,990		6,060		7,530		34,500		27,900	
Gain (or loss) Before U.S. Income Tax				M$ 3,390		(M$ 810)		(M$ 3,760)		M$ 1,330		M$ 8,140	

Source: Reference 25 (1971)

TABLE XLVIII

VALUE OF HSC FUELS, OFFSET TO CLEANING COST, PAYOUT OF INVESTMENT

Value of HSC Fuels:					
Taxable Gain (or Loss)	M$ 3,390	(M$ 810)	(M$ 3,760)	M$ 1,330	M$ 8,140
Gain (or Loss) After 48% Tax Effect	M$ 1,760	(M$ 420)	(M$ 1,960)	M$ 690	M$ 4,230
HSC Fuel Consumed - M Tons Per Year	640	410	300	2,300	2,100
Value of HSC Fuel - Per Ton	$ 2.75	($ 1.02	($ 6.53)	$ 0.30	$ 2.01
Offset to Coal Cleaning:					
Clean Coal Yield - M Tons Per Year	7,100	2,300	920	7,100	3,500
Credit (or Debit) Per Ton of Clean Coal	$ 0.25	($ 0.18)	($ 2.13)	$ 0.10	$ 1.21
Payout of Investment:					
Gain (or Loss) After 48% Tax Effect	M$ 1,760	(M$ 420)	(M$ 1,960)	M$ 690	M$ 4,230
Depreciation	1,634	1,662	1,752	7,169	7,214
Cash Flow	M$ 3,394	M$ 1,242	(M$ 208)	M$ 7,859	M$11,444
Total Investment	18,340	18,600	29,270	128,520	125,570
Payout - Years	5.4	15	---	16	11

Source: Reference 25 (1971).

by the adjustment costs is much more severe than ordinarily required in conventional coal-fired generators of comparable capacity. This is because of the high sulfur content and ash content of the reject materials used as fuel.

Sales income from energy and chemical values, after adjustment for pollution costs and other expenses, are then combined to form the total taxable income for each type of plant. A 48 percent income is applied to yield the net yearly gain for the plant of each design (Table XLVIII). Dividing this figure by the weight of high sulfur fuel consumed per year yields an estimate of the cost that the manufacturer could afford to pay for these fuels.

Table XLVIII indicates that three of the production plant designs (Cases A, D, and E) show net gains (sales price less total costs) ranging from $0.30 to $2.75 per ton of high sulfur fuel derived from HSC fuel utilization. This corresponds to pre-sales credits ranging from $0.10 to $1.21 per ton of the clean coal. In other words, the HSC fuel can be used for an economic advantage in addition to any profits gained from selling the low sulfur coal. Case B shows a net loss and therefore appears uneconomical. The prototype plant design, Case C, also shows a relatively high net loss and appears uneconomical as a production process. This is not surprising nor is it significant since Case C is a scaled-down version of Case D (which is economically feasible) and is intended to serve as a research and demonstration unit.

The economic analysis summarized in Tables XLV, XLVII, and XLVIII. does not present production costs and income on a strictly comparable basis, since Cases A, B, and E yield sulfuric acid as an end product, while Case D (and the scaled down version in Case C) yields elemental sulfur as an end product. The analysis of Case D was extended to include the conversion of sulfur to sulfuric acid and the marketing of the acid. An analysis similar to that of Tables XLVII and XLVIII shows that, under these conditions, the allowable price for high-sulfur fuel for the Case D plant would be about $2.00 per ton, which corresponds to a credit of about $0.97 per ton of clean coal.

This extension of the analysis indicates that the plant design for Case D is much more competitive with the design for Cases A and E than is apparent from the figures presented in Table XLVIII. In addition, the Case D design permits production of elemental sulfur or other acid intermediates as well as sulfuric acid, thereby providing a flexibility for adapting plant output to logistic and market conditions.

8.7 Findings

The following conclusions may be drawn from the Chemico study, supported by the research on high-sulfur fuel composition conducted by Bituminous Coal Research, Inc. (BCR):

- Any run-of-mine coal containing pyritic sulfur that can be processed to yield coal of lower sulfur content will also yield a fuel of higher sulfur content. The sulfur-to-coal

ratio of the high sulfur fuel can be controlled to any specification within wide limits.

- By using high-sulfur fuels of composition tailored to meet requirements of especially designed combustors and commercially available boilers, generators and sulfur-recovery processes, it appears possible to extract the energy and sulfur values of high-sulfur fuels on a commercially profitable basis.
- By appropriate selection of processing equipment, energy values may be realized in the form of electric power or industrial-quality steam and sulfur values may be in the form of sulfuric acid, elemental sulfur, or other intermediate compounds.
- In view of the high shipping costs resulting from the heavy weight of sulfuric acid, it is sometimes economically advantageous to ship sulfur in elemental form or as other compounds instead of the acid. The capability of a sulfur recovery plant to produce sulfur as several different compounds (or in elemental form) is therefore highly advantageous, especially in cases when the sulfur must be shipped to different points of consumption
- Preliminary design and analysis indicate that construction of a reduced-scale prototype would be warranted for research and development efforts required to evaluate the promising, but as yet undemonstrated, approach typified by the Case D design--large scale (500 mw) electric power generating capacity, with

versatile equipment for recovering sulfur in several alternative forms to meet various market and logistic situations. The need for demonstration of the capability to process high sulfur fuels in a commercially and environmentally acceptable manner is underscored by recent (1973) shortages of low-sulfur fossil fuels.

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16. ABSTRACT

The report provides an interpretative compilation of the overall EPA coal cleaning effort in the form of in-depth analysis, evaluation, and examination of the interrelationships among elements comprising the EPA coal program. The report basically addresses coal washability studies, sulfur reduction by cleaning processes including plant design and associated economics, and the utilization of reject sulfur and coal values from the cleaning processes.

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Air Pollution	Design Criteria	Air Pollution Control	13B, 14A
Coal	Economic Analysis	Stationary Sources	21D
Coal Preparation	Reclamation	Reject Sulfur	08I
Washing		Reject Coal Values	13H, 07A
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