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Project Summary

Computer Economics of Physical Coal Cleaning and Flue Gas Desulfurization

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Under EPA sponsorship, a computer model has been developed by TVA that determines process and detailed economic data for a physical coal-cleaning process and a limestone or lime flue gas desulfurization (FGD) process applied to electric utility boilers. The model can be used to determine the economics of either process used alone or the two in various combinations, based on user-supplied data on cleaning requirements, coal properties, and SO_2 emission requirements. The model also determines the indirect economic benefits and penalties to overall power plant operation associated with the use of cleaned coal. The coal-cleaning process consists of three processing streams in which coarse, medium, and fine coal fractions are cleaned by respectively, dense-medium vessels, dense-medium cyclones, and froth flotation. Several variants of the limestone or lime FGD process and different waste disposal methods can be specified for the FGD process. The model provides an analysis of the cleaned coal, a list of major FGD equipment, and detailed capital investment and operating cost data.

The report provides a general description of the model, illustrates its use and potential application, and summarizes its use in a large number of simulations. Using a 1,000-MW boiler as the basis, simulations were made with four coals at four cleaning levels and at four emission levels. The effects of these variables on the economics of the processes used separately and in combination are discussed.

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

Introduction

In recent years, coal cleaning has come to be regarded as a practical alternative in some cases for the control of SO_2 emissions from coal-fired power plants. TVA recently completed an economic evaluation for EPA that illustrated the potential of coal cleaning in SO_2 emission control. As a continuation of this program, a computer model was developed to model the performance and economics of full-scale coal cleaning alone and in combination with limestone and lime FGD. The model determines the process design and economics for a coal-cleaning process or a coal-cleaning process combined with FGD. It also determines the economic benefits and penalties attributable to the use of cleaned coal instead of raw coal.

The model should be useful in comparing process designs and economics of various combinations of coal-cleaning and lime or limestone FGD processes. This should be particularly useful when evaluating processes for specific applications since the model will illustrate the effect of changes in process variables on the cost and design of the component processes or the entire system as a whole.

Model Description

The coal-cleaning/FGD computer model consists of four computer programs (written in FORTRAN IV), linked by common input and output data. The first program determines process performance and economics of the coal-cleaning process from design and operating specifications; the second and third determine the FGD process design and the corresponding capital investment and annual revenue requirements from raw or clean coal properties and emission requirements; and the fourth quantifies selected economic benefits and penalties of using cleaned coal. Unlike the first three programs, which are modified versions of previously developed programs, the fourth was created specifically for this project. The cost elements that the model calculates include capital investment, first-year annual revenue requirements, and levelized annual revenue requirements: each can be generated for either a coal-cleaning process, a combined coal-cleaning/FGD process, or an FGD process, depending on user specifications. For the combined coal-cleaning/FGD process, the net cost is the sum of the costs for the coal-cleaning and FGD processes and the sum of the benefits and penalties.

Model Input Procedure

To simplify data entry for the combined model, all data required for its execution are included as input data to the coal-cleaning program. The information required includes power plant data, emission regulations, coal-cleaning process specifications, FGD design specifications, raw coal properties and washability, and economic data. The flow of the data throughout the combined model is shown in Figure 1.

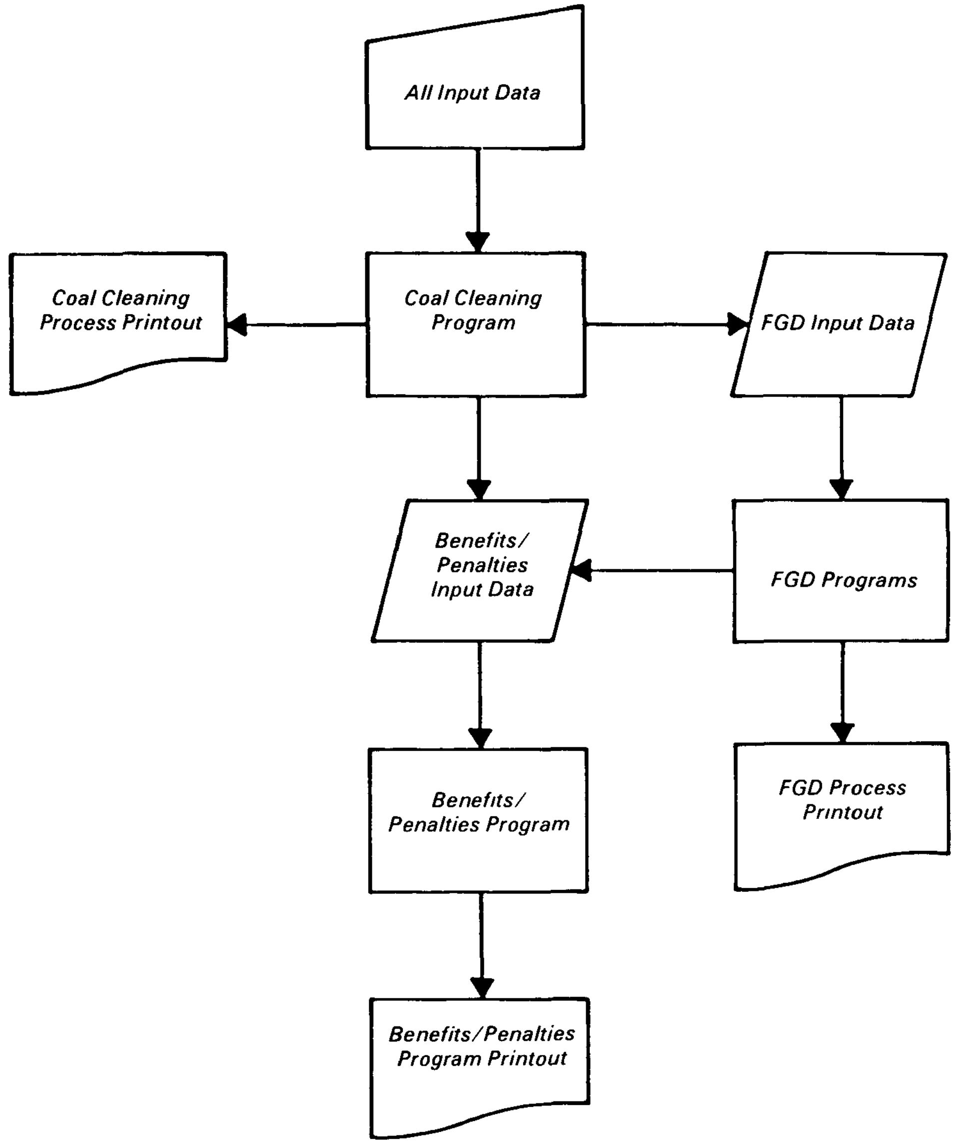

Figure 1. *Flow of data through the combined model.*

Coal-Cleaning Program

The coal-cleaning program was adapted from Battelle-Columbus Laboratories *Coal Preparation Simulation Model (CPSM4), Version 2.* The program required many modifications to conform to TVA's process design criteria and to form the combined coal-cleaning/FGD model. Although many of these changes were relatively minor and did not alter the program processing sequence, some areas required major revisions, requiring five new subroutines and associated program rearrangement.

The printout is divided into three segments: the first lists the values of selected input data to ensure that no errors were made during the input operation; the second (execution) provides an analysis of internal flow streams and a performance report for each equipment unit included in the coal-cleaning process; and the third presents the overall results of the simulation. The tables in this segment provide the performance data and the process economics for the coal-cleaning plant.

The model can simulate many coal-cleaning processes if equipment performance, process design information, and economic data are available. The base case process design used in the illustrative runs is felt to be typical. The flow diagram for this process design is shown in Figure 2. The process, as illustrated, separates the raw coal into three size fractions, each of which is processed in a different type of separation equipment: the coarse coal in a dense-medium vessel, the intermediate in a dense-medium cyclone, and the fine in froth flotation cells.

FGD Model

The FGD model is the Shawnee lime/limestone computer model developed by Bechtel National, Inc., and TVA using data obtained from the test facility at the TVA Shawnee Steam Plant near Paducah, KY. This model consists of two programs that produce full-scale design and economic data for a variety of limestone or lime FGD systems.

The current model includes options for limestone or lime scrubbing: a mobile-bed absorber (TCA), a spray tower or venturi-spray tower absorbers, and various waste disposal methods. The FGD process design used to illustrate the capabilities of the combined model is illustrated in Figure 3. The process employs limestone slurry scrubbing in a spray tower absorber and the untreated waste is disposed of in a pond.

Economic Benefits and Penalties Program

Many differences between cleaned and raw coal result in economic benefits and penalties for a power plant other than the obvious benefit of reduced FGD costs. This program utilizes appropriate equations to approximate many of these benefits and penalties that accrue because of such differences as a lower ash content, a higher moisture content, and generally a higher heating value of the cleaned coal. Each of the benefits and penalties calculated by this program is discussed below.

FGD Costs

The most important effect of coal cleaning on power plant costs is in the area of FGD costs; in some cases coal cleaning or coal cleaning with FGD can be more economical than FGD alone in controlling SO_2 emissions. The ways in which coal cleaning reduces the FGD requirement are much the same as the other benefits. In particular, the reduced sulfur content and increased heat content of cleaned coal reduce the quantity of SO_2 produced in the combustion process, thus reducing the SO_2 removal requirement of the FGD process. Sometimes the use of cleaned coal can even eliminate the need for FGD. The benefit that is used in this model is determined by comparing costs required when FGD is used to control raw coal combustion emissions with the FGD costs when the emissions from cleaned coal combustion are controlled.

Raw Coal Loss

No presently available coal-cleaning process can achieve 100% separation of pure coal from its impurities. Some coal is lost in the cleaning plant refuse, and some impurities remain in the cleaned coal. The coal that is lost is an economic liability for the coal-cleaning plant. This liability or penalty is quantified as the

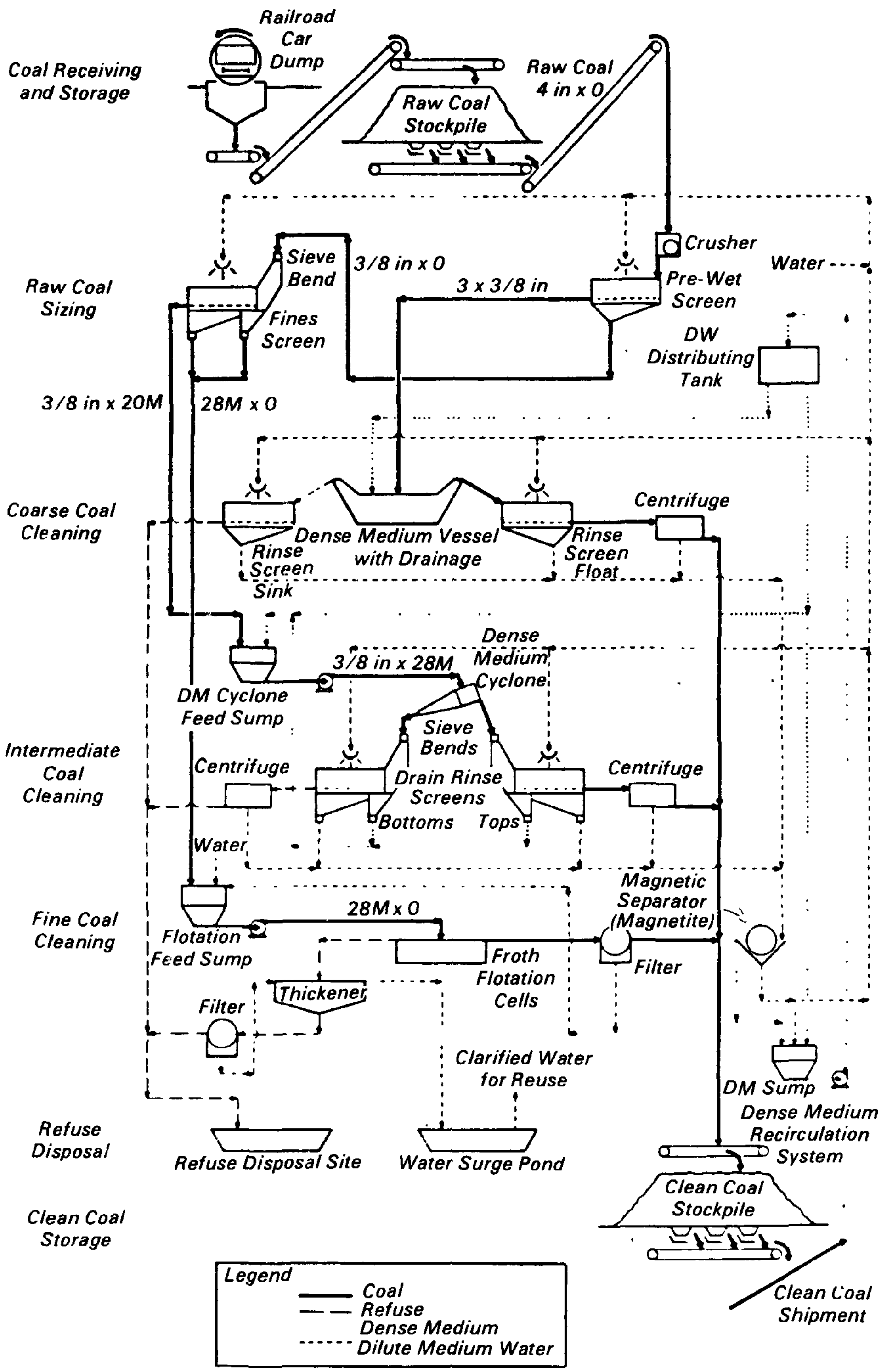

Figure 2. Flow diagram for the coal-cleaning process.

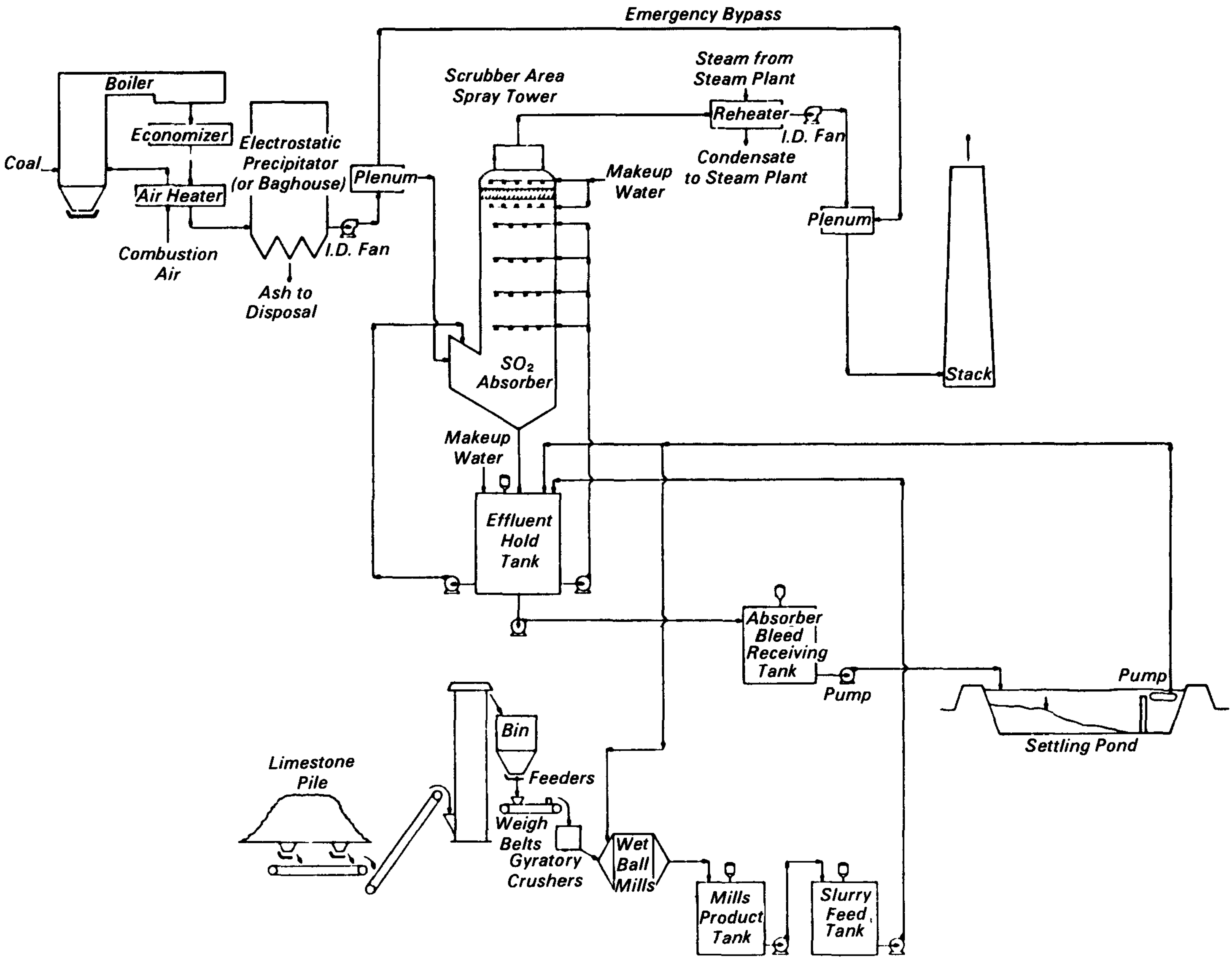

Figure 3. *Flow diagram for the limestone-scrubbing process.*

heat content (Btu's) of the coal that is lost in the refuse.

Transportation Costs

In most cases coal cleaning produces a product that has a higher heating value than the raw coal, thereby reducing the quantity of coal necessary to satisfy the heat requirements of a specific power plant. When coal is cleaned at the mine, the reduced coal requirement decreases the cost of transporting the coal, which is a cost benefit for the utility.

United Mine Workers' Benefits

The 1978 United Mine Workers' (UMW) contract requires mine operators to pay $1.385 to the Pensions and Benefit Trust Fund for every ton of coal shipped to a consumer. Since coal cleaning generally reduces the quantity of coal required by a power plant, the contribution to the trust fund is also reduced, resulting in a cost benefit for the utility.

State Taxes

State-imposed coal taxes, often called severance taxes, are presently levied by 13 states. Depending on the method of taxation, coal cleaning can reduce or increase these taxes, creating a cost benefit or penalty. At present, there are four ways to apply these charges: taxation based on the tonnage of coal shipped is the most common. For this reason, it is used in the example runs for this project. Based on this method, coal cleaning would generally yield an economic benefit by reducing the quantity shipped. On the other hand, taxation based on the tonnage mined or value of the coal shipped would produce an economic penalty for coal cleaning because of the coal loss in the cleaning plant refuse.

Size Reduction

In general, at least two and sometimes three size reductions are performed on coal as it moves from the ground to the power plant boiler. For the development of this program, it was assumed that the power plant was equipped with pulverized coal boilers, in which case three size reductions are necessary. The first reduction is at the mine: the run-of-mine (ROM) coal is crushed to the appropriate topsize. The next two reductions are at the power plant: the coal is crushed before being fed to the pulverizers and then ground into powder in the pulverizer and fed to the boiler. When coal cleaning is used, an additional size reduction is usually included, resulting in a cost benefit to the utility because the size reduction requirements at the power plant are reduced. Coal cleaning can also produce a benefit in the size reduction operations at the power plant by reducing the coal mineral matter, making the coal easier to grind. Also, the increased heating value of cleaned coal decreases the amount to be ground. One effect of coal cleaning, the increase in surface moisture, can increase pulverizer plugging, but it is not considered in the program because of lack of data on the effects of moisture.

Maintenance Costs

The quality and quantity of the coal used in a power plant have long been recognized as having a direct effect on the maintenance costs of the plant equipment. Some of the equipment areas have been mentioned, but other areas which must be considered include the boilers and accessories, coal conveying and storage equipment, and the air heaters. Coal cleaning yields an economic benefit in maintenance costs for these and other areas of power plant operation by raising the quality of coal burned in the plant and by reducing the ash and sulfur content. To quantify this benefit, the program uses a relationship based on the ash and sulfur in the coal which is derived from actual power plant maintenance data.

Power Plant Availability

The availability of a power plant for the production of electricity is another area that is affected by the use of cleaned coal. Many of the factors relating to availability (e.g., tube corrosion, sootblower failure, slagging, and fouling) are influenced by power plant age and mineral content of the coal burned; therefore, they are also influenced by the use of cleaned coal. It is difficult to quantify the effects of coal cleaning on availability because of the influence of other factors unrelated to fuel quality. In the program, the availability benefit is quantified, using a logarithmic relationship based on the coal ash content, sulfur content, and boiler age.

Boiler Efficiency

The efficiency of a power plant boiler is often expressed in terms of the amount of heat required to generate 1 kWh of power. This characteristic of the power plant is affected by coal cleaning in much the same manner as availability, except that: (1) the increased surface moisture, inherent in cleaned coal, reduces boiler efficiency, and (2) the coal sulfur content does not appreciably affect efficiency. Of the three factors affecting efficiency (moisture content, ash content, and boiler age), the coal moisture content effect is the most pronounced. All of these factors are included in the equation used by the model to quantify this benefit (or penalty).

Electrostatic Precipitation

The major factor controlling the size and cost of an electrostatic precipitator (ESP) is the specific collection area, which is determined primarily by the fly ash resistivity and volumetric flow rate of flue gas. Fly ash resistivity is directly related to such factors as ash content, ash composition, and sulfur content of the coal. Volumetric flow rate is related to the coal composition: carbon content, hydrogen content, sulfur content, ash content, and moisture content. Coal cleaning, by altering coal properties, also affects ESP capital and operating costs. In most cases, the results are detrimental: an economic penalty is imposed.

Ash Disposal

The costs of transporting and disposing of the ash are decreased because coal cleaning reduces the ash content of the coal and generally increases the heating value of the coal, both of which decrease the quantity of ash to be disposed of at the power plant.

Design and Economic Premises

The design and economic premises for the combined coal-cleaning/FGD model are based on premises developed by TVA for economic evaluations of power plant emission control processes. The premises for the benefits and penalties program were developed especially for this model.

The base case assumes a new, midwestern, 1,000-MW, pulverized-coal-fired power plant supplied by a coal-cleaning plant at a mine 500 miles* away, with transportation by unit train. The design heat rate of the boiler is 9,200 Btu/kWh, and it operates at full load for 5,500 hours a year for 30 years. The coal-cleaning process incorporates three cleaning streams: dense-medium vessels for coarse coal (3 in. x 3/8-in.), dense-medium cyclones for medium-sized coal (3/8-in. x 28 mesh), and froth flotation for fine coal (less than 28 mesh).

The cases studied are based on four coals, selected characteristics of which are presented in Table 1 with the equivalent SO_2 contents. Each coal is cleaned by controlling the specific gravity of the separating media at 1.40, 1.50, 1.60, and 1.80. The emission standards evaluated consist of 0.6, 1.2, 2.0, and 4.0 lb $SO_2/10^6$ Btu emission limits and the 1979 new source performance standards (NSPS).

The economic premises are based on regulated utility operations. Capital investments, first-year annual revenue requirements, and levelized annual revenue requirements are determined. The costs are projected to 1982 for the capital investment and to 1984 for the annual revenue requirements.

Results and Examples of Model Use

To test the computational accuracy of the model, selected results from the model output have been compared with the corresponding results obtained from manual calculations. This comparison yields a maximum difference of less than 1.5%, which is well within acceptable limits.

The results obtained from this model can be used in many different ways, including:

- To determine the most economical method of SO_2 control using coal cleaning, FGD, or a combination of both.
- To illustrate the effects of changes in process conditions on the performance and economics of a coal-cleaning, an FGD, or a combined coal-cleaning/FGD process.
- To analyze the effect of coal cleaning on power plant operations by considering various benefits and penalties attributable to coal cleaning.

*Readers more familiar with metric units may use the conversion factors at the back of this Summary.

- To compare the process performance and economics for different coal-cleaning and FGD process designs.

These do not exhaust all possible uses, but they do indicate potential uses of the model.

The main objectives of this report are to make potential users of this model aware of its availability and to illustrate some of its possible uses. To accomplish the latter, the model was used to simulate a range of conditions. Eighty runs were made using the four premise coals, each cleaned at four specific gravities of separation, with the flue gas restricted to five SO_2 emission limits. Other trial runs of the combined model were made by varying such conditions as cleaned coal topsize, power plant megawatt rating, and the distance from the cleaning plant to the power plant.

Coal-Cleaning Operating Performance

In a coal-cleaning plant, the specific gravity of the medium in the cleaning vessel is usually controlled to regulate the properties of the cleaned coal. For this reason, it is the input variable used in the model to define the cleaning process operating conditions. Among the important plant performance parameters determined by the specific gravity are the yield, the reduction in sulfur emission, and the Btu recovery. The yield (weight of clean coal product divided by the weight of raw coal feed) is an indirect measure of the amount of material which is mined, processed, and later discarded as refuse. The reduction in sulfur emission parameter is a function of the reduction in ash and pyritic sulfur as determined by the physical desulfurization (washability) of each coal. The Btu recovery is the percentage of the Btu content of the raw coal that remains when the coal is cleaned. It is a measure of both the cleaned coal properties and the economics of the process since the Btu loss in the refuse is an important economic factor in coal cleaning.

The relationships between specific gravity of separation and the resulting yield reduction in sulfur emission parameter and Btu recovery are shown in Table 2. Yield and Btu recovery decrease as the specific gravity of separation decreases. This is to be expected because the amount of ash and pure coal lost to the cleaning plant refuse increases as the specific gravity decreases. The sulfur reduction increases as the specific gravity decreases due to the increased pyritic sulfur removed. The result is a tradeoff between high-Btu recovery and high-sulfur removal.

Table 1. *Selected Characteristics and Equivalent SO_2 Contents of the Premise Coals*

Coal	*Pyritic Sulfur, %*	*Total Sulfur, %*	*Ash, %*	*Moisture, %*	*Heat Content, Btu/lb*	*Equivalent SO_2 Content in Coal, lb $SO_2/10^6$ Btu*
Illinois No. 6	*3.27*	*4.34*	*29.39*	*1.36*	*9,667*	*8.97*
Pittsburgh	*2.15*	*3.67*	*13.81*	*3.42*	*12,121*	*6.05*
Upper Freeport	*1.88*	*2.32*	*16.80*	*5.60*	*11,668*	*3.97*
Cedar Grove	*N.A.*	*0.85*	*16.04*	*6.60*	*11,680*	*1.45*

Basis: All values are on an as-received basis.

Table 2. *Sulfur Reduction and Btu Recovery by Coal Cleaning*

	Raw Coal	*Coal-Cleaning Operating, Specific Gravity 1.4*	*1.5*	*1.6*	*1.8*
Illinois No. 6 Coal					
Yield, %	-	*56*	*65*	*68*	*73*
lb $SO_2/10^6$ Btu[a]	*8.97*	*3.86*	*4.18*	*4.38*	*5.08*
Sulfur reduction, %	-	*57*	*53*	*51*	*43*
Btu recovery, %	-	*78*	*88*	*92*	*96*
Pittsburgh Coal					
Yield, %	-	*73*	*83*	*86*	*91*
lb $SO_2/10^6$ Btu[a]	*6.05*	*3.79*	*4.18*	*4.37*	*4.68*
Sulfur reduction, %	-	*37*	*31*	*28*	*23*
Btu recovery, %	-	*82*	*92*	*95*	*97*
Upper Freeport Coal					
Yield, %	-	*67*	*78*	*82*	*88*
lb $SO_2/10^6$ Btu[a]	*3.97*	*1.76*	*1.93*	*2.03*	*2.35*
Sulfur reduction, %	-	*56*	*51*	*49*	*41*
Btu recovery, %	-	*78*	*89*	*93*	*97*
Cedar Grove Coal					
Yield, %	-	*78*	*80*	*81*	*83*
lb $SO_2/10^6$ Btu[a]	*1.45*	*1.17*	*1.20*	*1.23*	*1.25*
Sulfur reduction, %	-	*19*	*17*	*15*	*14*
Btu recovery, %	-	*91*	*93*	*95*	*96*

[a]*Assuming 100% conversion of sulfur to SO_2.*

FGD Operating Performance

The FGD process design used in this illustration removes 90% of the SO_2 in the flue gas that is scrubbed. If the overall SO_2 removal requirement of the FGD system is less than 90%, a portion of the gas is bypassed to allow the scrubber to operate at the 90% removal level. The bypassed flue gas is then combined with the scrubbed flue gas to reduce the steam requirements for reheating (which is often the single largest energy requirement of an FGD process). For this reason, the amount of bypass is the most important FGD operating condition affecting the FGD design. The portion of flue gas bypassed is determined by the emission limit, the heating value, the sulfur content of the fired coal, and the sulfur content of the ash.

Economics

One possible use of the combined computer model is to determine the combination of coal cleaning and FGD that will meet a specified emission limit at the minimum overall cost. The operating conditions for this optimum combination are not the same for every case because they can change with variations in coal properties, process characteristics (e.g., washing equipment efficiencies), and the particular cost element chosen for the analysis.

Capital Investment

The changes in capital investment for coal-cleaning, FGD, and the other economic benefits and penalties are shown as a function of Btu recovery in Figure 4. These cases are for Pittsburgh coal with a 1.20 lb $SO_2/10^6$ Btu emission limit. In terms of change in capital investment, coal cleaning has a large effect on FGD. The net capital investment, considering all three components, is lower for the combined coal-cleaning/FGD process than for FGD alone over much of the range of coal-cleaning conditions used. The minimum in the net capital investment curve indicates that an optimum set of cleaning conditions does exist with respect to capital investment. For the conditions used in Figure 4, the minimum occurs at a Btu recovery of approximately 75%. The specific gravity of separation equivalent to this recovery represents the conditions at which the system should be designed to minimize capital investment.

Annual Revenue Requirements

The levelized annual revenue requirements for the same cases are shown in Figure 5. Coal cleaning has the same general effect on FGD annual revenue requirements as it has on FGD capital investment—a continuing decline as the level of coal cleaning increases. For the other benefits and penalties, however, there is an initial decline, followed by rapidly increasing annual revenue requirements (because of the Btu loss) as the coal-cleaning level increases. The combined coal-cleaning/FGD process thus has lower annual revenue requirements than FGD alone only for a certain range of coal-cleaning conditions—in this case from about 80% to near 100% Btu recovery. Thus, the decision to use coal cleaning with FGD often depends on the other economic benefits and penalties that are associated with coal cleaning.

Comparing the curves in Figures 4 and 5, each curve has a minimum cost point, but these minimums do not exist at the same Btu recovery. The curve for the net capital investment has a minimum at approximately 75% Btu recovery, while the net annual revenue requirements curve has a minimum at 93% Btu recovery. The shift in minimum cost point for the annual revenue requirements is largely due to the large effect of Btu loss on annual revenue requirements as Btu recovery decreases. The minimum point depends on the value assigned to the coal lost in the refuse: in this example, a cost of $20.81/ton was used; a different cost would correspondingly shift the minimum point toward a lower or higher Btu recovery.

Figure 6 illustrates the reduction in levelized annual revenue requirements for the four coals at different SO_2 emission limits as compared to sulfur removal with FGD alone. Significant differences in levelized annual revenue requirements result from differences in coal washability. Also, the economics generally become more favorable as the SO_2 emission limits become less stringent; however, the curves for the Cedar Grove and Upper Freeport coals do have a maximum point beyond which the economics become less favorable. These maximums are at the points where the optimum pollution control process changes from a combined coal-cleaning/FGD process to a coal-cleaning process, alone. The curves for the Illinois No. 6 and Pittsburgh coals did not reach the point at which coal cleaning could provide the most economical pollution control process without some degree of FGD being necessary.

Project Conclusions and Recommendations

A computer model able to calculate the economics of coal-cleaning processes alone and combined with FGD in utility applications has been developed. Selected values from the model agreed closely with those from manual calculations.

The illustrative runs using four premise coals had coal-cleaning sulfur removals from 14% to 57% and met some less stringent emission limits without FGD. The combined coal-cleaning/FGD process for each coal had a specific gravity of separation at which costs were at a minimum. Coal cleaning reduced the FGD costs in all cases, primarily by allowing more flue gas to be bypassed. In some cases, this reduction in FGD costs offsets the costs of coal cleaning. Case-by-case comparisons must be made to determine the most economical approach.

For the cases studied, it was found that the use of coal cleaning in combination with FGD can have a varied effect on the levelized annual cost of power production. This effect, which depends on the coal and the specific operating conditions, ranges from a 0.5% increase to a 22.6% decrease.

The methods used to determine many of the other economic benefits and penalties of coal cleaning are necessarily

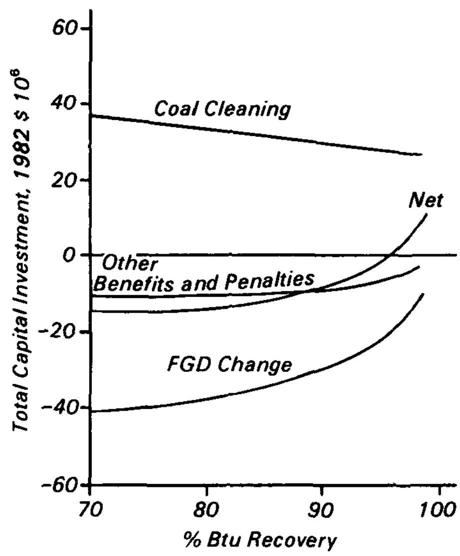

Figure 4. *Effect of Btu recovery on the net total capital investment. Pittsburgh coal at 1.20 emission limit.*

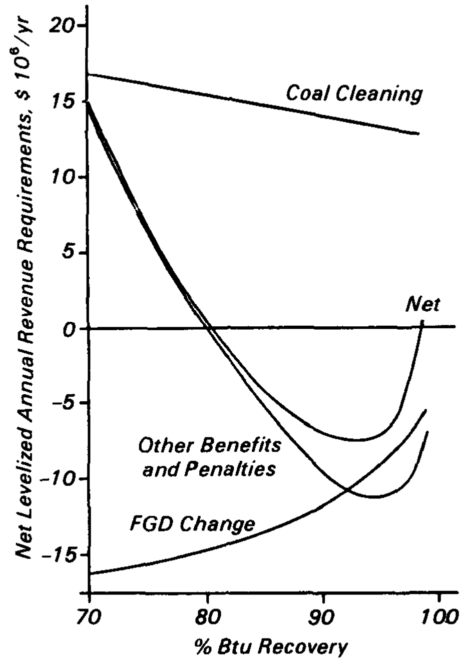

Figure 5. *Effect of Btu recovery on the net levelized annual revenue requirements, Pittsburgh coal at 1.20 emission limit.*

general in nature because detailed data relating specific coal properties to boiler performance and operating costs are scarce. Thus, development and incorporation of more detailed and quantitative data in the model would greatly increase the usefulness of the model in assessing overall economic effects of coal cleaning. Similarly, the scope of the model could be increased by incorporating other coal-cleaning processes and alternate emission control processes such as fabric filter baghouses and spray dryer FGD and by modifying the functions to allow multiple simultaneous simulations. The economics of retrofit situations should also be considered.

Conversion Factors

Readers more familiar with the metric system may use the following to convert the nonmetric units used in the Summary:

Nonmetric	Times	Yields Metric
Btu	1.055	kJ
in.	2.54	cm
lb	0.454	kg
mi	1.609	km
ton	907.2	kg

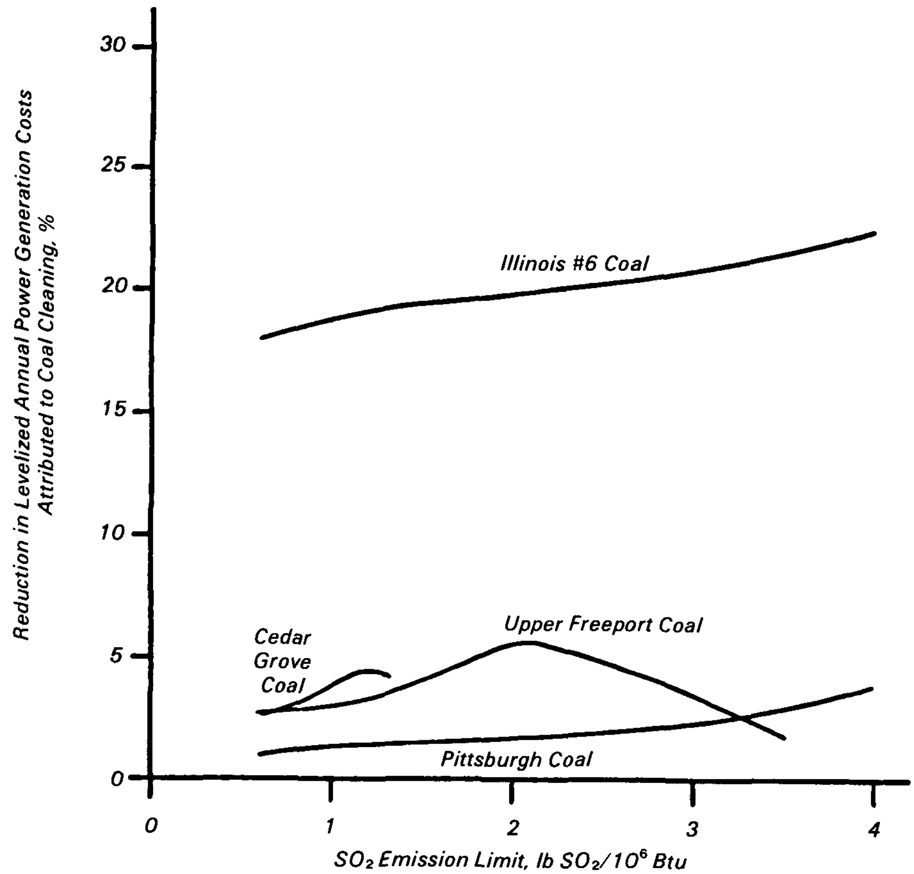

Figure 6. *Effect of emission limit on the power generation cost reduction attributable to coal cleaning (at optimum specific gravity), compared to sulfur removal with FGD alone.*

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The complete report, entitled "Computer Economics of Physical Coal Cleaning and Flue Gas Desulfurization," (Order No. PB 86-156 452/AS; Cost: $16.95, subject to change) will be available only from:

National Technical Information Service
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