CROSS-MEDIA ENVIRONMENTAL IMPACTS OF COAL-TO-ELECTRIC ENERGY SYSTEMS

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Abstract

The types and rates of pollutant emissions from coal utilization systems depend on process design, coal characteristics, and environmental control technology. The latter is strongly influenced by environmental regulatory policy which has historically focused on pollutant emissions to a single environmental medium (air, land, or water) without rigorous analysis of the energy and secondary environmental impacts that follow. It thus remains unclear as to whether regulations requiring stringent control of single pollutants in a single medium may actually be counterproductive to overall environmental quality when energy and cross-media impacts are considered. The present paper describes an approach being developed at Carnegie-Mellon University to systematically address such issues in the context of conventional and advanced technologies producing electricity from coal. Analytical models are described which compute system residuals to air, land, and water as a function of coal parameters and system design after all ancillary energy penalties are accounted for. Included are models of a coal cleaning plant, flue gas desulfurization system, dry particulate collector, wastewater control system, and low-Btu gasification plant coupled to either a conventional or combined cycle power generation system. Application of these models is illustrated in the context of alternative regulatory strategies for sulfur dioxide emission control. Methodologies for assessing cross-media tradeoffs in the context of societal value judgments are also discussed.

INTRODUCTION

Increasing interest in the use of coal as an energy source has sharpened our awareness of the close relationship between energy technology development and environmental regulatory policy. Environmental regulations limiting gaseous and liquid discharges from coal utilization systems can have significant ramifications on the cost and feasibility of specific processes. At the same time, adequate environmental control is imperative if the adverse effects of coal utilization are to be mitigated. The goal of informed public policy is to develop regulations and standards that provide acceptable environmental protection in a way that is equitable to competing energy processes. This requires that environmental regulatory policy be sensitive to adverse effects in all environmental media (air, land, and water), and that it also be sensitive to the impact specific regulations can have on the viability of alternative coal technologies. Both concerns suggest the need for a comprehensive "systems" view of the environmental impacts of coal conversion technologies. This paper describes the status of work at Carnegie-Mellon University to develop such a model for coal-to-electric systems, including advanced coal conversion processes. Results are presented following a review of current regulatory policy for coal conversion technologies.

REVIEW OF CURRENT REGULATORY POLICY

A 1975 paper by Rubin and McMichael[1] summarized the nature and status of regulations and standards affecting coal utilization processes. For air and water pollutants two types of standards exist: standards of ambient environmental quality, and standards limiting source emissions. For air, environmental quality standards include national primary and secondary ambient air levels designed to protect human health and welfare. Special standards also prevent the significant deterioration of superior air quality. For water, environmental quality standards are similarly designed to protect human health and welfare as well as aquatic species in streams and rivers. While ambient air quality standards apply uniformly across the nation (except where state and local standards are more stringent), ambient water standards vary markedly from stream to stream. They are set principally by state and local agencies subject to federal approval. Uniform standards for drinking water, however, now apply nationally.

Discharge standards for air and water pollutants are the principal enforcement tool for achieving standards of environmental quality. Existing sources are regulated by state and local agencies. New sources of certain industrial categories are regulated federally via New Source Performance Standards (NSPS) promulgated by the U.S. Environmental Protection Agency (EPA). These require the use of Best Available Control Technology (BACT) for specified air and/or water pollutants. For most processes, they pose an important design constraint which adds to the cost of technology.

At the present time, no NSPS regulations exist for synfuel processes, though regulation of process sulfur emissions from Lurgi hi-Btu gasification plants is being considered by EPA.(2) Table 1 summarizes the air and water pollutants currently regulated by NSPS for coal-fired steam-electric generators, petroleum refineries and by-product coke plants. The latter two may be suggestive of future coal refineries producing synthetic gas or liquid from coal. Regulation of solid waste effluents from coal utilization systems is currently subject to state and local standards only. Federal regulations in the solid waste area is limited to special situations such as mining and ocean dumping, although increased regulation is likely as a result of the 1976 Solid Waste Recovery Act.

TABLE 1

POLLUTANTS REGULATED BY FEDERAL NEW SOURCE PERFORMANCE STANDARDS

Substance	Steam-Electric Generators	Petroleum Refineries	By-Product Coke Plants
AIR POLLUTANTS			
Carbon Monoxide		x	
Hydrocarbons		x	
Nitrogen Oxides	x		
Particulate Matter	x	x	P
Sulfur Dioxide	x	x	
Total Sulfur		P	
Hydrogen Sulfide		P	
WATER POLLUTANTS			
Ammonia		x	x
Biochem, Oxygen demand		x	x
Chemical Oxygen demand		x	
Chlorine Residual	x		
Chromium	x	x	
Corrosion Inhibitors	x		
Cyanides			x
Heat	x		
Oil and Grease	x	x	x
pH	x	x	x
Phenols		x	x
Sulfide		x	x
Total Organic Carbon		x	x
Total Suspended Solids	x	x	x
Zinc	x	x	
Copper	x		
Iron	x		
Phosphorus	x		

P = Proposed

Multimedia Impact of NSPS Regulations

The choice of technology and the energy penalty incurred in meeting New Source Performance Standards gives rise to what we call "cross-media" environmental impacts. This refers to situations in which the reduction of a pollutant emission to one environmental medium (air, land, or water) increases the pollutant burdens in other media. Some examples of this are well known; e.g., solid waste disposal problems resulting from FGD systems at electric power plants. Other cross-media impacts may be less obvious. Control systems that require additional steam or electricity to operate cause additional fuel to be burned resulting in increased emissions to the air, water, and land. Current environmental regulatory policy does not generally incorporate such cross-media impacts in a rigorous way. Rather, regulations typically focus on only a single pollutant emitted to a single medium.

An example of this is the NSPS for sulfur dioxide emissions from new steam generators. The current standard of 1.2 pounds per million Btu heat input to the boiler precludes direct combustion of coal without some type of pretreatment or post-treatment process in most cases. Currently available options are coal beneficiation (mechanical cleaning) and flue gas desulfurization (FGD). Alternative technologies are coal conversion processes producing clean gaseous or liquid fuels, such as low-Btu gas which can be burned directly as a boiler fuel or used in a combined cycle electric generating station. No NSPS yet exists limiting SO_2 emissions from combustion of gaseous fuels derived from coal. However, Table 2 shows that existing local, State, and Federal standards for other types of low-Btu gas containing hydrogen sulfide restrict emissions to levels an order of magnitude less than the NSPS for coal. This reflects the availability of technology to desulfurize low-Btu gas more extensively than is possible in combustion gases. A policy requiring best available control technology when burning low-Btu gas would substantially reduce SO_2 emissions relative to a conventional coal-fired system. However, one price of doing so might be a more energy intensive (as well as more expensive) technology, with greater multimedia impacts. This is illustrated quantitatively later in the paper.

Finally, current new source standards do not necessarily regulate the same pollutant in the same way in different processes. An example is the difference in the way wastewater effluent limitations are imposed on petroleum refineries and by-product coke manufacturing plants, two currently regulated processes that bear similarities to coal conversion plants. Table 3 shows that in most respects the structure of current regulations for these two processes differ substantially even though most of the regulated pollutants are identical, and the level of allowable emissions are similar when normalized on the input fossil fuel energy content. The structure of future regulations for coal gasification and liquefaction plants is more uncertain since the zero discharge goal of the 1972 Federal Water Pollution Control Act may require complete recycling of all wastewaters from these facilities. Again, cross-media environmental impacts (on land and air) will result from wastewater control strategies. These must be anticipated in the design of wastewater regulations.

TABLE 2

SELECTED SO_2 EMISSION STANDARDS FOR COMBUSTION OF FOSSIL FUELS

Source Category	Maximum Allowable Emission (lbs $SO_2/10^6$ Btu)*		
	Solid	Liquid	Gas
Federal Standards (NSPS)			
Fossil-fueled steam Generators	1.2	0.8	–
Petroleum refinery plant gas	–	–	0.11^A
State and Local Standards			
Coke oven gas (Allegheny County, PA)	–	–	0.19^B
Fossil-fueled Steam generators			
(New Mexico)	0.34		0.16^C
(Wyoming)	0.2		–

[A] From H_2S combustion assuming 250 Btu/scf (9.3 mJ/m^3)

[B] From H_2S combustion assuming 700 Btu/scf (26.1 mJ/m^3)

[C] For power plant associated with coal gasification plant

*1.0 lb/10^6 Btu = 0.430 kg/gJ

TABLE 3

COMPARISON OF FEDERAL WASTEWATER EFFLUENT STANDARDS

Petroleum Refineries	By-Product Coke Plants
Limits on 1-day and 30-day max.	Limits on 1-day and 30-day max.
Based on emission per unit of plant feedstock input	Based on emission per unit of plant feedstock output
Limits vary with plant size and complexity	Same limits for all plant sizes and complexity
Limits applicable to "end-of-pipe" (includes total plant)	Limits applicable only to coking process (not total integrated steel mill)

METHODOLOGICAL NEEDS FOR REGULATION DEVELOPMENT

The discussion above suggests a number of policy research questions that the authors have raised previously in the context of regulatory policy implications for synthetic fuel plants.[1] These include questions as to how plant type, size, complexity, and product mix should enter the regulatory picture; whether limits on pollutant discharge should be established for individual unit operations or for larger systems, including the total plant; whether environmental regulations can be structured so as to reward process improvements that reduce environmental impact; and whether a multi-media approach that minimizes overall environmental impact can be developed into a workable regulatory scheme.

Evaluation of environmental tradeoffs, however, is a difficult task. An idealized framework for such an analysis is suggested in Figure 1. The three principal elements involve: (a) characterizing the rates and types of emissions to air, water, and land as a function of the coal feed type and the characteristics of process and environmental control technologies; (b) examining how these emissions are transferred through various media (air, land, and water) to receptors in the environment (humans, plants, and animal life); and (c) evaluating the damage incurred by these receptors from exposure to the various pollutants. This type of methodology would yield a benefit/risk/cost analysis of alternative regulatory standards, in contrast to the existing philosophy of NSPS which is based only on best available technology. The framework is idealized, however, since our current state of knowledge is simply inadequate to actually perform this type of analysis. Indeed, even the characterization of coal conversion process emissions cannot yet be done rigorously in many cases.

Three research programs in progress at Carnegie-Mellon University (CMU) seek to improve methodologies for assessing coal conversion plant environmental impacts and regulatory policies. One effort involves the measurement and characterization of waste streams from ERDA pilot plants producing high-Btu gas from coal.[3] This program will contribute a substantially improved data base for assessing advanced technologies and the implications of alternative policy formulations. A

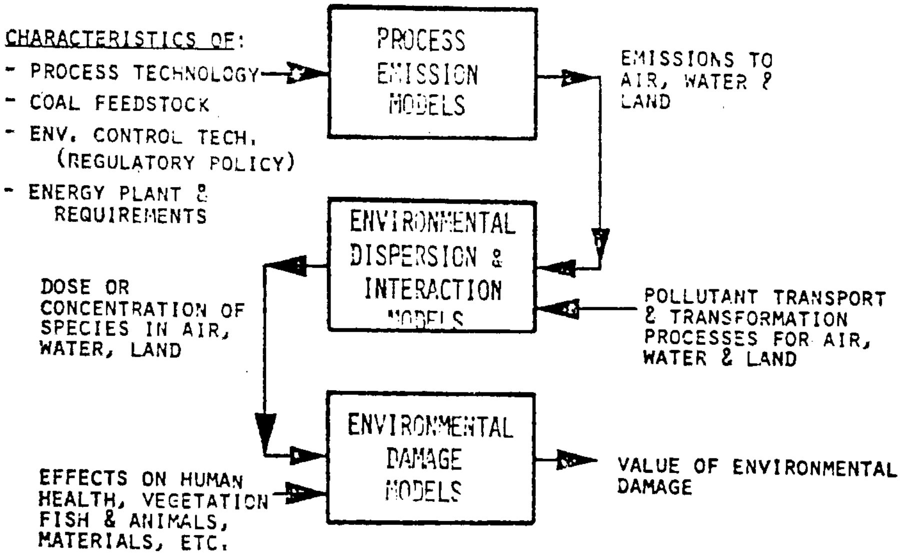


Figure 1. An idealized framework for standards development.

second program is directed at assessing the environmental damage of pollution with particular emphasis on the role of uncertainty. To date, this research has focused on the health effects of sulfur dioxide emissions from coal-fired power plants.[4] A third effort, which is the subject of the present paper, involves the development of a systematic framework for characterizing air, water, and land emissions from coal utilization technologies as a function of four factors:

- coal characteristics,
- process and environmental control technology characteristics,
- environmental regulatory constraints, and
- useful product or output.

This represents the first module in Figure 1. The emission inventories derived from this analysis are basic to any subsequent approach to integrate their impact on air, land, and water. Currently, work is focused on conventional and advanced coal-to-electric systems, which represent the greatest potential for coal use in the near term.

COAL-TO-ELECTRIC SYSTEMS MODEL

A systematic framework for comparing alternative coal-to-electric technologies is illustrated in Figure 2. The figure applies to a mine mouth situation using run-of-mine (ROM) coal in one of several ways. One is to burn the coal directly in a conventional steam-electric generator using once-through cooling and no flue gas cleanup. This would represent an environmentally uncontrolled or "base case" situation. A system designed to meet environmental standards would be more complex. To meet water effluent standards for heat, suspended solids, organics, and other chemical species a wastewater treatment system including cooling towers or pond would replace simple once-through cooling. To meet air pollution standards, a flue gas treatment system or coal cleaning prior to combustion would be required. Flue gas treatment could include a desulfurization system (FGD) and/or a particulate removal device (mechanical collector, electrostatic precipitator or baghouse). Precombustion cleanup could include

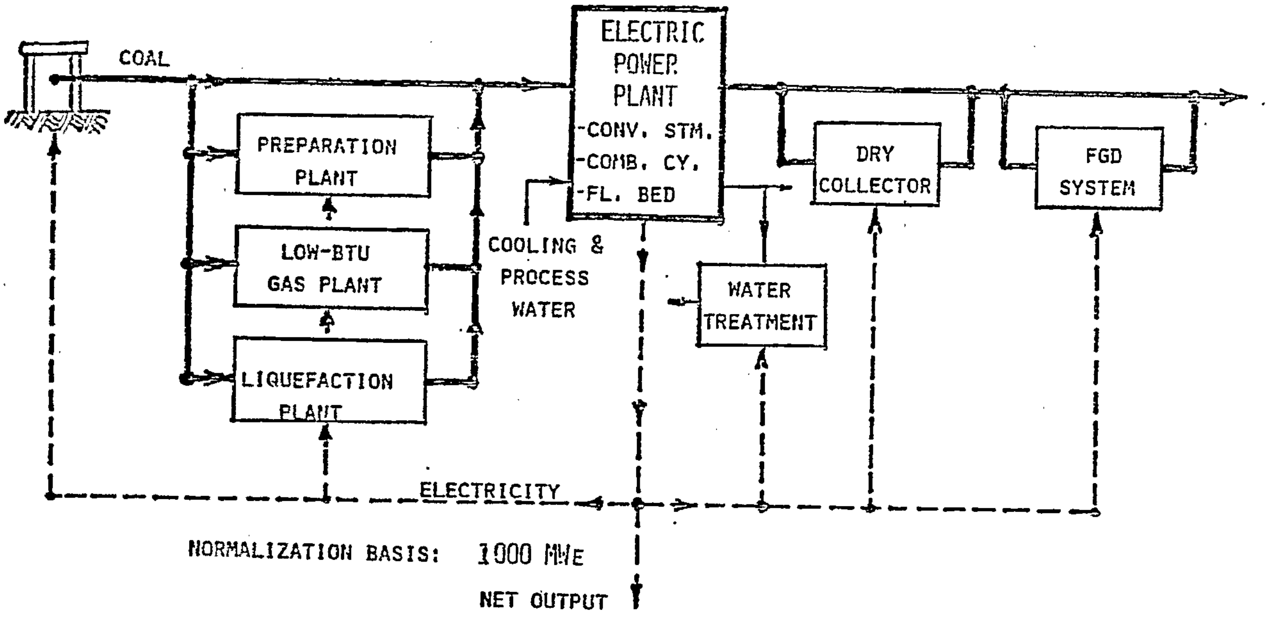


Figure 2. CMU systems model of coal-to-electric technologies.

mechanical coal cleaning or conversion of coal to a clean gaseous or liquid fuel. Advanced technologies such as fluidized bed boilers offer the potential for direct combustion of coal with simultaneous pollutant removal.

All the alternatives above have two important characteristics. First, in meeting environmental regulations for air and water pollutants additional residual streams appear that may pose new environmental problems. Secondly, each component or system alters the thermal efficiency of the coal-to-electric cycle, directly affecting all material flow rates (including effluents to air, land, and water) associated with the production of power. From an environmental point of view, the systems model in Figure 2 asserts that the proper basis for comparing different coal-to-electric generating systems is on the ability to produce the same amount of electricity for sale after all ancillary energy needs are accounted for. For convenience this quantity is taken as 1000 MW. Electricity is thus viewed as a socially desirable commodity and the environmental impacts of different systems producing it are compared on the basis of *a common net output*. From this perspective, a number of technical and policy issues can be addressed as indicated in Table 4. The goal of on-going research at CMU is to develop computerized

TABLE 4

EXAMPLES OF ENVIRONMENTAL IMPACT TRADEOFF ISSUES ADDRESSED BY PARAMETRIC ANALYSIS USING CMU MODEL

Useful Electrical Output	Coal Characteristics	Emissions Contraints	Process and Env. Control Tech. Characteristics	Types of Questions Addressed
Constant	Varied	Constant	Derived	What process and/or control technology characteristics are needed to comply with fixed emission constraints for various coals? What are the associated coal production rates, costs, and emissions of pollutants to air, land and water from producing a fixed amount of electricity for sale?
Constant	Derived	Constant	Varied	What coals can be used to comply with given emission regulations for different processes or facility configurations? What are the associated costs and emissions?
Constant	Derived	Varied	Constant	What coals can be used at a given type of facility as emission constraints are changed? What are the associated costs and emissions?
Constant	Varied	Derived	Constant	What regulations are required in order to use certain types of coal at a given facility? What are the associated costs and emissions?
Constant	Constant	Varied	Derived	What facility characteristics are required to process a given coal for various emission constraints? What are the associated costs and emissions?
Constant	Constant	Derived	Varied	What must the emission constraints be for various facilities in order to process a given coal? What are the associated costs and emissions?

analytical models of the modules in Figure 2 which are sufficiently detailed to capture all pertinent factors, but which are also sufficiently simple and flexible so that a wide range of parameters can be examined easily. The following paragraphs present highlights of the models currently developed. Following this is an illustration of their use to examine the multimedia impacts of alternative formulations of SO_2 regulations for coal-based electric power systems.

Coal Feedstock Parameters

Four coal characteristics are the principal parameters of the model. These are the coal higher heating value, ash content, sulfur content, and pyrite fraction expressed on a dry mass basis. More detailed data on coal composition (ultimate analysis) is used to model the performance of FGD and low-Btu gasification systems. The electrical energy penalty required to mine coal (applicable to underground mining) is also an optional parameter of the model.

Coal Preparation Plant

Mechanical cleaning of coal prior to combustion is modeled in terms of either a "simple" plant, designed principally for ash reduction with maximum energy yield and some sulfur reduction, or a "complex" plant providing greater sulfur reduction but with higher material and energy losses. Figure 3 shows the latter configuration. Wash circuits are provided for coarse and fine coal, with the fine stream reporting to a thermal dryer to achieve an acceptable moisture content in the final coal mixture. In the analytical model, ash, sulfur, and energy recovery are functions of the overall material yield (which depends on bath specific gravity) and the crushed coal top size. The model employs coal-specific washability curves of the type reported by the U.S. Bureau of Mines for various domestic coal seams.(5) Electrical energy is required by the plant for coal crushing, particulate control equipment, materials handling, liquid pumping, and wastewater treatment. These requirements are evaluated and modeled in proportion to the coal flow in various circuits. The thermal dryer incurs an additional energy penalty modeled as a fraction of the ROM coal input. Air pollutant emissions from the dryer incorporate empirical data on adsorption of SO_2 on the dried coal and levels of NO_x emissions. Dryer TSP emissions are controlled to the NSPS level assuming use of a wet scrubber. Solid waste from the cleaning plant occurs as a dewatered sludge principally containing ash, sulfur, and coal refuse. All other waters are assumed to be completely recycled.

Figure 4 illustrates the sulfur reduction achieved for three eastern coals "processed" through the CMU coal cleaning plant model. In this case the plant was designed to recover 90 percent of the input coal mass with coal crushed to 3/8" top size. 63-68 percent of the sulfur was pyritic. The plant achieved an overall reduction of 38 to 41 percent in total sulfur expressed as equivalent SO_2 per unit energy content of coal. Between 3 and 8 percent of the coal energy was lost as plant refuse.

Steam-Electric Generator

The nominal steam-electric system assumed in the CMU model employs a pulverized coal boiler designed to achieve NSPS levels of NO_x emissions. The primary electrical conversion efficiency is represented as a gross cycle heat rate, defined as the electrical generator output excluding any energy needed to run coal production and environmental control systems. The primary coal pulverizer is treated separately since its energy requirement decreases when coal is mechanically cleaned prior to combustion. A penalty for nitrogen oxide control can be included if boiler modifications such as air preheater bypass are needed to achieve emission standards.

Coal ash and sulfur streams are partitioned between the bottom ash and flue gas streams while thermal heat loss is divided between air and water. This determines the emissions of an uncontrolled plant. Emissions of carbon monoxide, hydrocarbons and nitrogen oxides are calculated from empirical emission factors for the assumed boiler type. Solid waste streams from an uncontrolled plant are assumed to occur as boiler bottom ash and sludge from the feedwater treatment unit. These are calculated by mass balance and empirical effluent factors, respectively. Uncontrolled effluents to receiving waters include thermal and

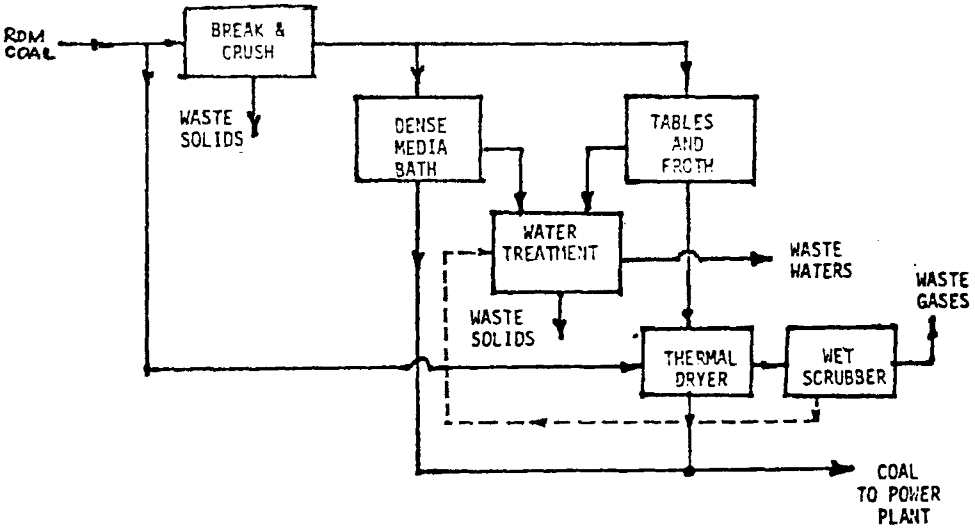


Figure 3. Schematic of coal cleaning plant model.

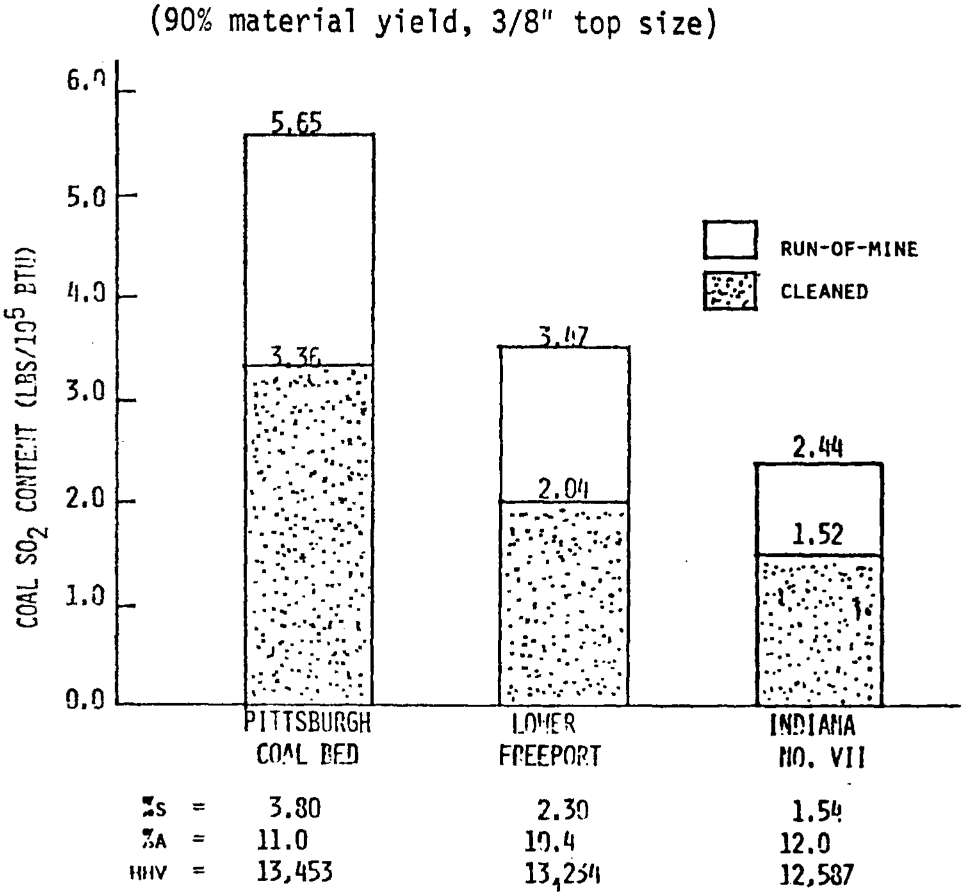


Figure 4. Sulfur content of three eastern coals "cleaned" by model plant.

chemical discharges plus suspended solids. These are estimated from available data on power plant characteristics.

Particulate Collection System

Flyash is assumed to be collected in a dry collection system and/or a wet scrubber incorporated as part of an FGD system. The dry collector can be an inertial separator, baghouse, or electrostatic precipitator. Performance is represented in terms of a collection efficiency with an associated energy penalty expressed as a fraction of gross power plant output. The mass flow rate of solid waste is determined by a mass conservation algorithm that includes a specified moisture content for slurried systems.

Flue Gas Desulfurization System

The performance of an FGD system can be modeled simply by specifying an SO_2 removal efficiency and associated energy penalty. Alternatively, a detailed analytical model has been developed which calculates FGD energy requirements for a nonregenerative limestone system, which is the most prevalent FGD technology today. This model is similar to one developed by the Tennessee Valley Authority (TVA) for cost estimation in lime/limestone FGD systems,(6) and employs performance correlations developed by Bechtel and TVA. The schematic of Figure 5 shows the major elements of the model. Where dry particulate collection is used, partial bypass of the scrubber can be implemented to achieve current SO_2 emission standards by treating only a fraction of the gas to a higher SO_2 removal efficiency than needed if the entire flue gas stream is scrubbed. Sensitivity analyses have shown that this can result in significant energy as well as cost savings.(7) Energy penalty calculations incorporate raw material and sludge-handling costs as well as electrical requirements for all gas-phase and liquid-phase fans and pumps plus steam requirements for gas reheat.

Figure 6 illustrates the fact that FGD energy requirements increase nonlinearly as SO_2 emissions are decreased. The figure also indicates how higher sulfur coals incur greater energy penalties to achieve a given SO_2 emission standard. The absolute level of energy needed depends on a number of coal, plant, and system parameters as suggested in Table 5. The principal secondary enviromental impact of lime/limestone technology is sludge consisting principally of calcium sulfate, calcium sulfite, flyash, and limestone with appreciable moisture content. Regenerative systems that eliminate sludge disposal incur a significantly larger energy penalty. This increases the air

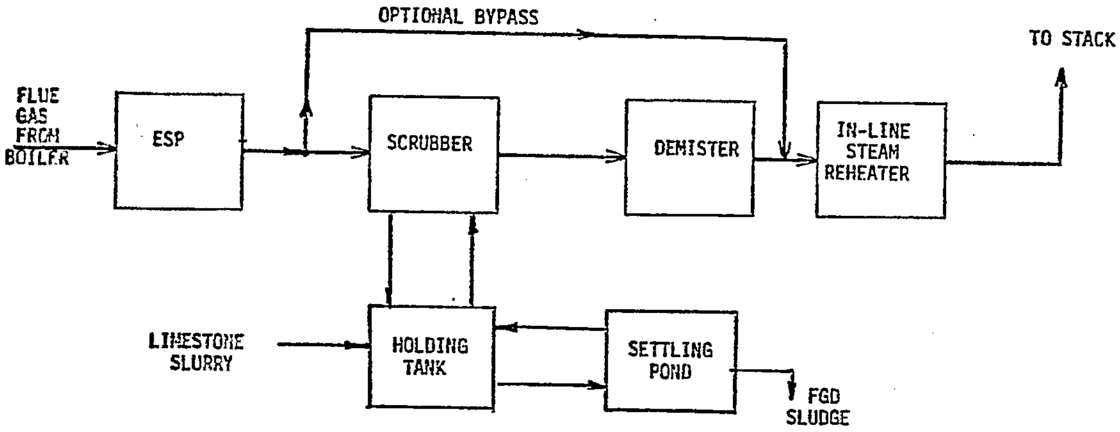


Figure 5. Schematic of limestone FGD system.

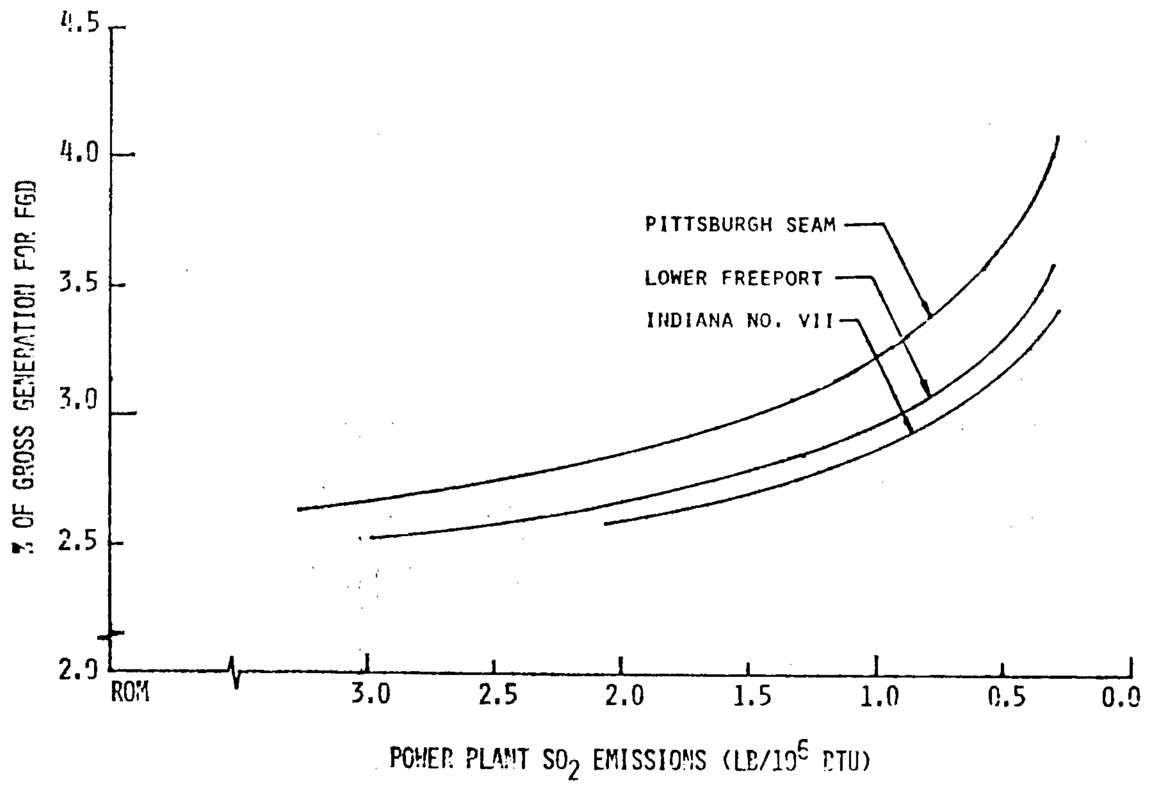


Figure 6. **FGD system energy requirements for three eastern coals.**

TABLE 5

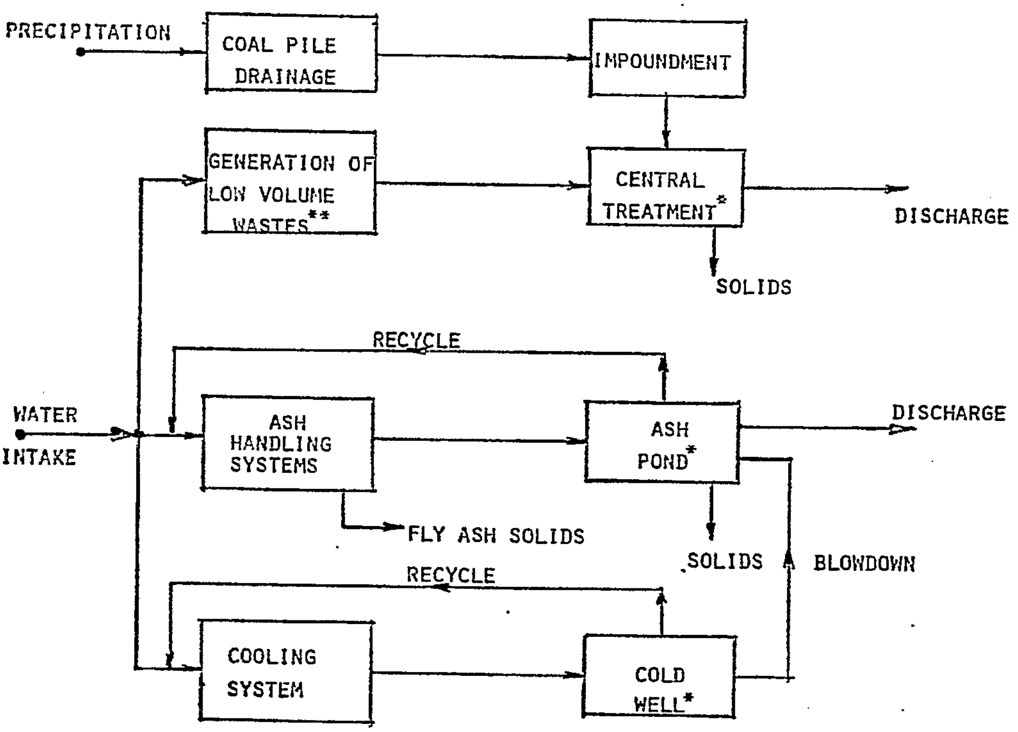
EFFECT OF SYSTEM PARAMETER VARIATIONS ON LIMESTONE FGD SYSTEM ENERGY REQUIREMENTS (Ref. 6)

Parameter	One Percent Increase in Nominal Value	Resulting Percent Increase in FGD Energy*
Stack exit temperature	1.75°F	2.3
Coal heating value	105 Btu/lb	-1.6
Coal sulfur content	0.035%	0.7
SO_2 emission regulation	0.012 lb/10^6 Btu	0.52
Entrainment at demister	0.001% gas wt.	0.45
Scrubber inlet temperature	3.0°F	-0.4
Gross plant heat rate	90 Btu/KWH	-0.1

pollutant and ash emissions per unit of net electrical output.

Water Treatment System

Water treatment systems for conventional steam-electrical power plants are designed to achieve effluent standards for heat, suspended solids, and other chemical constituents (see Table 1). The principal component is a cooling tower which transfers waste heat from the water to the air. This system incurs an energy penalty modeled principally in terms of the water pumping head, cooling range, and increase in turbine back-pressure imposed by the tower. Schemes for the treatment of chemical wastes are modeled in different forms depending on whether the cooling water treatment



*COAGULANTS MAY BE ADDED

**INCLUDES BOILER BLOWDOWN, EQUIPMENT CLEANING WASTES (BOILER TUBES, BOILER FIRESIDE, AIR PREHEATER, STACK, COOLING TOWER BASIN), RAINFALL RUNOFF, SANITARY WASTES, PLANT LAB AND SAMPLING STREAMS, INTAKE SCREEN BACKWASH, AND FLOOR DRAINS.

Figure 7. Water treatment for a controlled plant using a recirculating system.

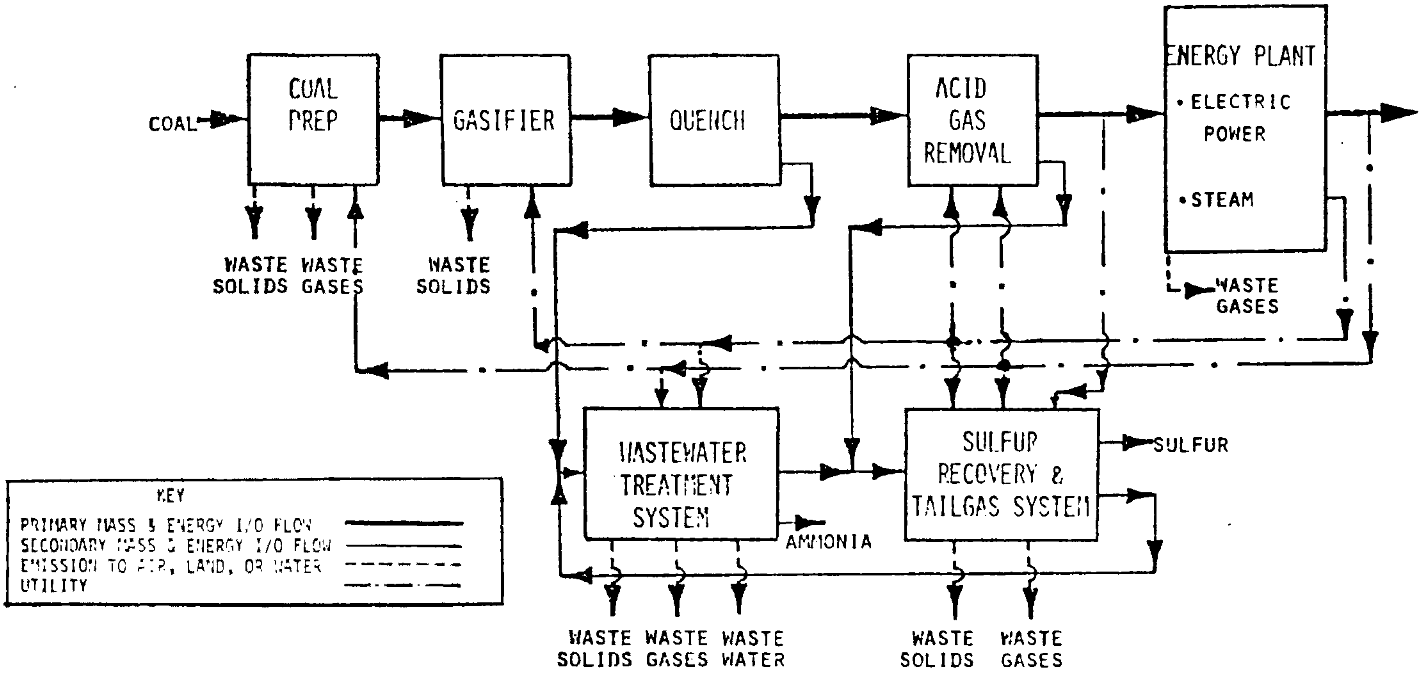
system is of the recirculating or once-through type. One example is shown in Figure 7. Note that treatment of chemical waste transforms potential wastewater effluents into sludges to be disposed on land.

Coal Gasification/Combined Cycle System

A potential alternative for using coal to produce electricity is to first gasify it, then use the low-Btu gas either as a boiler fuel in a conventional Rankine cycle or in a combined cycle system having the advantage of a higher thermodynamic efficiency. Although commercial low-Btu gasifiers are available the combined cycle approach has yet to be successfully demonstrated. Nonetheless, electricity from coal via low-Btu gas could become an attractive alternative to direct combustion if theoretical efficiency advantages can be realized economically.

A generic model of a low-Btu gasification plant (Figure 8) has been developed from published studies of various processes.(8-12) Run-of-mine coal first enters a preparation stage where it is crushed and sized. Pretreatment (mild oxidation) may also occur at this point when using agglomerating coals. Coal is then introduced into the gasifier with additional water (steam) and air to generate crude product gas. This gas is cooled in a quench stage to remove heavy liquids, particles, and other im-

Figure 8. Energy and mass flows for low-Btu coal gasification/combined cycle model.



SOME POTENTIAL POLLUTANTS FROM SYNTHETIC FUELS PLANT

AIR	WATER	LAND
SO_2	NH_3	ASH SLURRIES
TSP	ΦOH	FINES
NO_x	CN	DRY RESIDUES
CO	SCN	WASTE TREATMENT SLUDGES
C_xH_y	BOD	SPENT CATALYST
H_2S	COD	SLAGS
COS	TOD	
NH_3	TSS	
HCL	TDS	
HCN	pH	
TRACE METALS	HEAT	
CARCINOGENS	OILS	

purities. The cleaned gas then proceeds to the acid gas removal step where the sulfur concentration is reduced to an acceptable level dictated by environmental regulatory policy. The gas can then be fired in a boiler or utilized in a combined cycle system to produce electric power. Waste gases are exhausted to the atmosphere just in a conventional plant. The two major environmental control systems introduced by the low-Btu gasification process are the wastewater treatment system and the sulfur removal/recovery system.

Wastewater Treatment. The characteristics of raw wastewaters from advanced coal gasification plants are not yet well characterized although some pilot plant data are becoming available.[13,14] Table 6 suggests that while there is some simlarity among gasification process effluents there are also marked differences from one process to another that can significantly affect the level of type of wastewater treatment technologies. In general, treatment will include oil-water separation; steam stripping to remove hydrogen sulfide (which is sent to the sulfur recovery system); ammonia (recovered as a by-product) and other acid-producing dissolved gases; and removal of organic compounds, particularly phenols, using an absorption system (for wastewaters with low organic content) and/or a biological oxidation system (for wastewaters with high organics). A polishing process may also follow. It remains unclear, however, as to what level of treatment will apply to commercial gasification plants. Presently, these are subject only to State and local standards, which vary considerably. Rubin and McMichael[1] showed that Federal NSPS standards for by-product coking and petroleum refinery—two processes resembling coal gasification plants—are similar when compared on the basis of fossil fuel energy input to the process (Table 7). It remains speculative as to whether this might also apply to coal gasification processes. Several processes under development call for the complete recycle of wastewaters to improve the process design as well as to comply with potential zero discharge requirements for liquid waste.

In terms of the cross-media problem, the important point to emphasize is that control or elimination of wastewater constituents aggravates air and land problems indirectly via the need to produce additional electricity and steam, as well as directly through the production of gaseous and solid waste discharges (sludges) from various unit operations. Electrical energy penalties are incurred in pumping wastewaters through the various treatment steps, while steam is needed for stripping

TABLE 6

WASTEWATER CHARACTERISTICS OF THREE COAL CONVERSION PROCESSES

(Ref. 14)

POLLUTANT	Synthane Process PDU, (North Dakota Lignite)	Hygas Process Pilot Plant (Montana Lignite)	By-Product Coke Comm'l Plant (Bituminous)
Ammonia	19.5 ± 3.0	13.1 ± 0.3	8.5
Phenol	11.9 ± 1.2	11.4 ± 2.4	0.9 - 1.0
Chemical Oxygen Demand	77.7 ± 14.4	N/D	4.0 - 5.5
Total Organic Carbon	22.0 ± 3.0	39.1 ± 15.4	1.6 - 2.0
Cyanide	Negligible	Negligible	0.02 - 0.05
Thiocyanate	0.05 ± 0.08	2.5 ± 0.2	0.3 - 0.4
Tar	74.1 ± 27	~0	93
Light Oil	N/A	N/A	33
Total Dissolved Solids	N/A	12.4 ± 0.06	N/A

TABLE 7

ADJUSTED NEW SOURCE PERFORMANCE STANDARDS FOR BY-PRODUCT COKE MAKING AND PETROLEUM REFINING

(30-Day Maximum) (Ref. 1)

(pounds of pollutant per 10^{12} Btu feedstock)

Pollutant	Petroleum Refineries	By-Product Coke Making
BOD 5	210-2900	N/A
TSS	140-1920	600
COD	1050-20,000	N/A
Oil & Grease	70-890	240
Phenolics	1.5-19	12
Ammonia as N	40-1700	240
Sulfide	1.1-16	5.8
Total Chromium	3.5-47	N/A
Hexavalent Chromium	0.06-0.80	N/A
Cyanides amenable to Chlorination	N/A	5.8

* Assumes heating values of 6.5 million Btu/bbl for crude oil and 12,000 Btu/lb for coal, with a coke yield of 0.69 lb coke/lb coal.

N/A = not applicable.

operations. This steam may or may not represent an energy penalty, depending on details of process design. This is illustrated quantitatively later in this paper. In all cases, the magnitude of the ancillary energy demand is proportional to the quantity of wastewater treated.

Sulfur Removal and Recovery. Whereas high-Btu gasification processes must remove virtually all gaseous sulfur to prevent poisoning of catalysts and maintain gas quality, removal of sulfur from low-Btu gas producing steam or electricity is needed only to comply with environmental standards. As many as three unit operations may be involved in controlling sulfur emissions: acid gas removal, primary sulfur recovery, and tail gas cleanup system. Figure 9 shows how the energy penalty for increased desulfurization increases nonlinearly for one acid gas removal system in widespread use.(15) Table 8 shows the overall energy requirement incurred in product gas desulfurization using several systems analyzed for the EPA. Environmental impacts of desulfurization may occur as gaseous emissions notably sulfur compounds from the tailgas treatment system and solid waste generation in the form of sludges

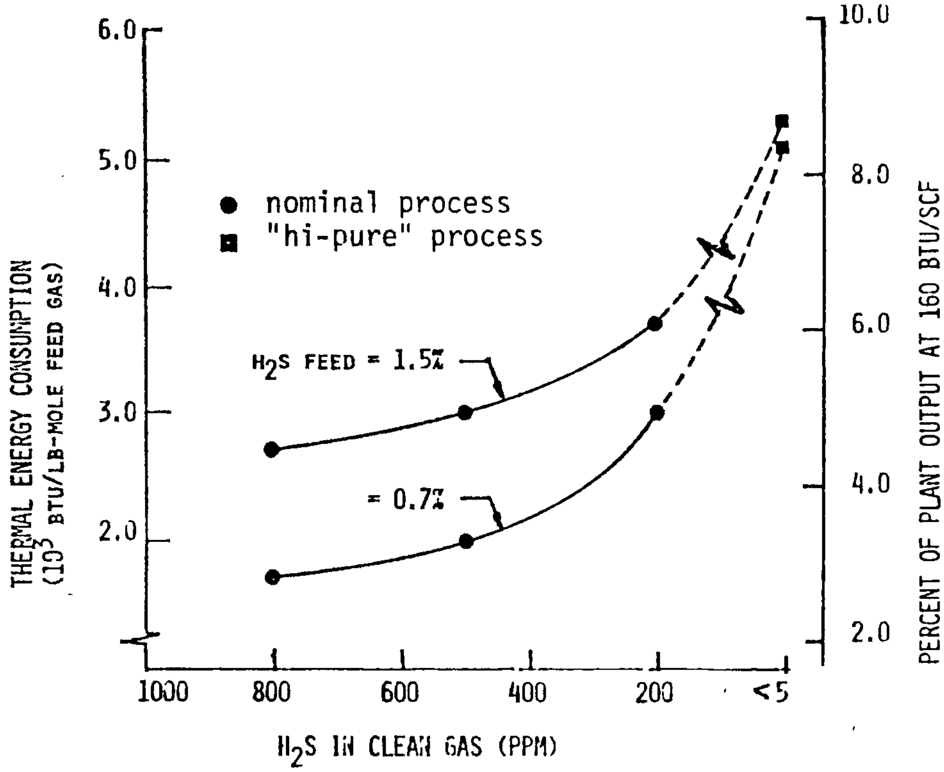


Figure 9. Thermal energy requirement for acid gas removal (Benfield Process) (Ref. 20).

TABLE 8

LOW-BTU GASIFICATION PLANT
4.5% Sulfur Feedstock, 137 x 10^3 GJ/day
ENERGY REQUIREMENTS FOR SULFUR REMOVAL/RECOVERY*
(As a percent of product gas output)

Process Component	Hot Potassium +Claus Plant +Beavon Tailgas	Hot Potassium + Claus Plant +Wellman-Lord TG	Iron Oxide +Allied Plant +Beavon Tailgas
Sulfur Content =	0.7 KG/GJ (0.3 lb $SO_2/10^6$ Btu)	0.7 KG/GJ (0.3 lb $SO_2/10^6$ Btu)	3.0 KG/GJ (1.2 lbs $SO_2/10^6$ Btu)
SULFUR RECOVERY			
Electricity	1.91	1.91	9.60
Steam	9.34	9.34	–
Sub-Total	11.25	11.25	9.60
TAILGAS CLEANUP			
Electricity	0.28	0.48	0.12
Steam	0.04	0.17	0.02
Auxiliary Fuel	0.61	5.11	0.09
Sub-Total	0.93	5.76	0.22
Total Gas Energy	12.2%	17.0%	9.8%
GJ/10^3 KG·S Removed	64.7	92.0	59.0
Plant Cost–¢/GJ	20.2	24.3	32.4
(¢/10^6 Btu)	21.3	25.6	34.2

*Derived from Ref. 9 assuming efficiencies of 40% for electricity, 85% for steam and 100% for auxiliary fuel.

and spent catalyst. Additional liquid waste may be generated and sent to the wastewater control section.

APPLICATION OF ANALYTICAL MODELS

Impact of SO_2 Emission Regulations

The models described above can be used to systematically compare the multimedia impacts of different technologies generating electricity, as well as the cross-media effects of alternative regulatory strategies. To illustrate this, consider the regulation of sulfur dioxide emissions from a conventional power plant burning a high sulfur eastern coal (Pittsburgh seam, Figure 4). Define a "base case" plant configuration as one with no desulfurization technology and no cooling tower or water treatment system producing 1000 MW net output. Compare this to an equivalent environmentally controlled plant that meets Federal new source standards for water pollutants, and controls SO_2 emissions to some specified value expressed as mass emission per unit heat input to the boiler. Figure 10 shows that water pollutants are now virtually eliminated while the SO_2 mass emission is reduced up to 90 percent depending on the emission level that is specified.

Cross-media consequences of these emission reductions are shown in Figures 11-15, assuming use of cooling towers and limestone FGD.

Figure 11 shows an increase in the net cycle heat rate of the power plant corresponding to a decrease in overall thermal efficiency from about 38 percent for the base case plant to about 33 percent for a controlled plant meeting NSPS levels for water and SO_2 emissions (Figure 12). If the coal is mechanically cleaned before combustion the FGD energy penalty is reduced but the overall cycle heat rate (mine-to-busbar) is still higher because approximately

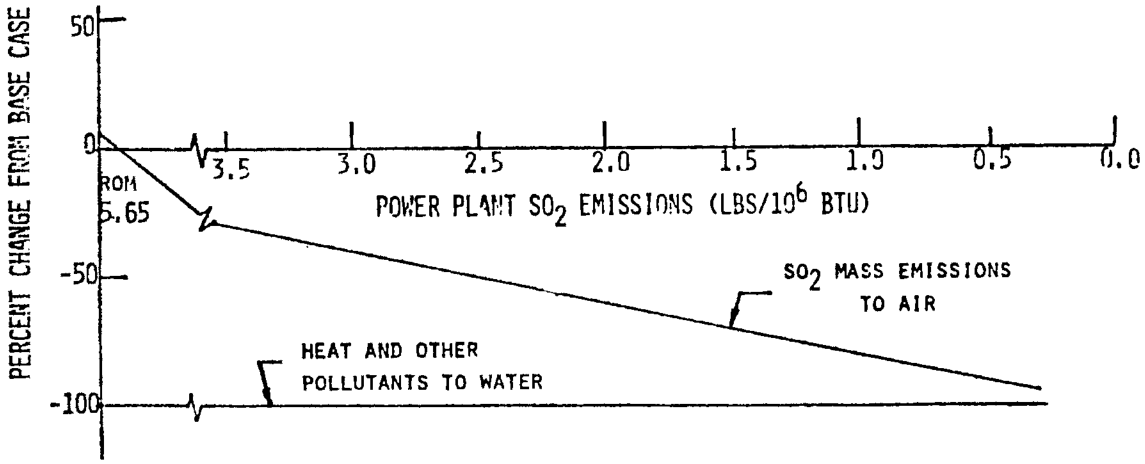


Figure 10. Effect of emission standards on base case SO_2 and water pollutant emissions. (Pittsburgh seam coal)

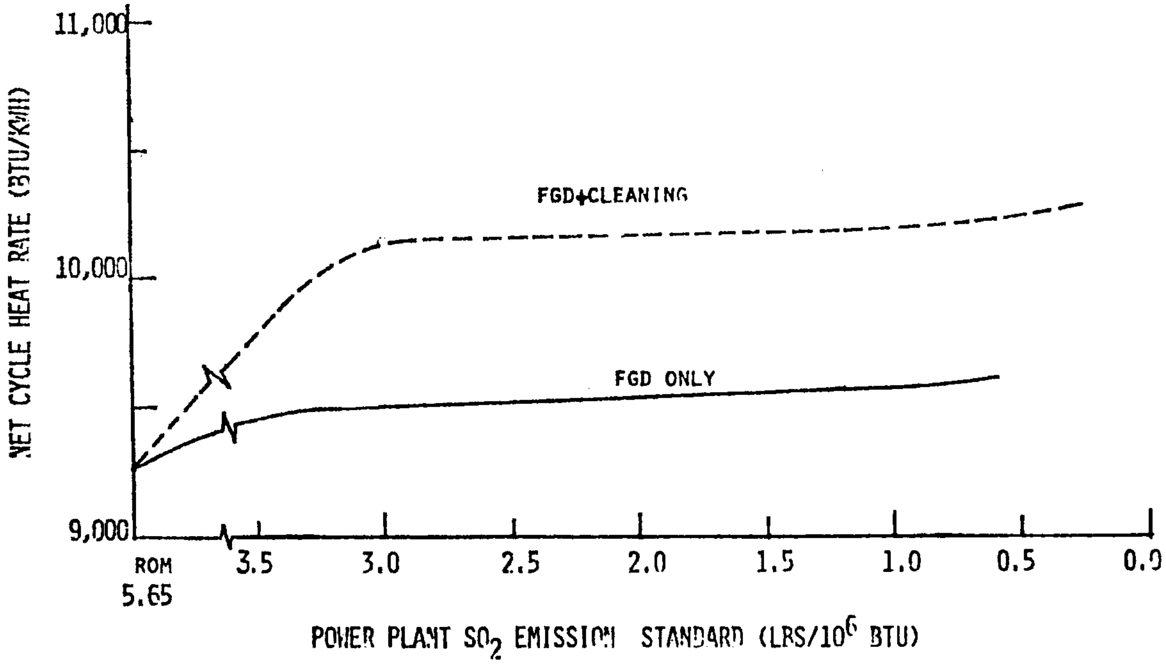


Figure 11. Effect of SO_2 emission standard on net cycle heat rate. (Pittsburgh coal)

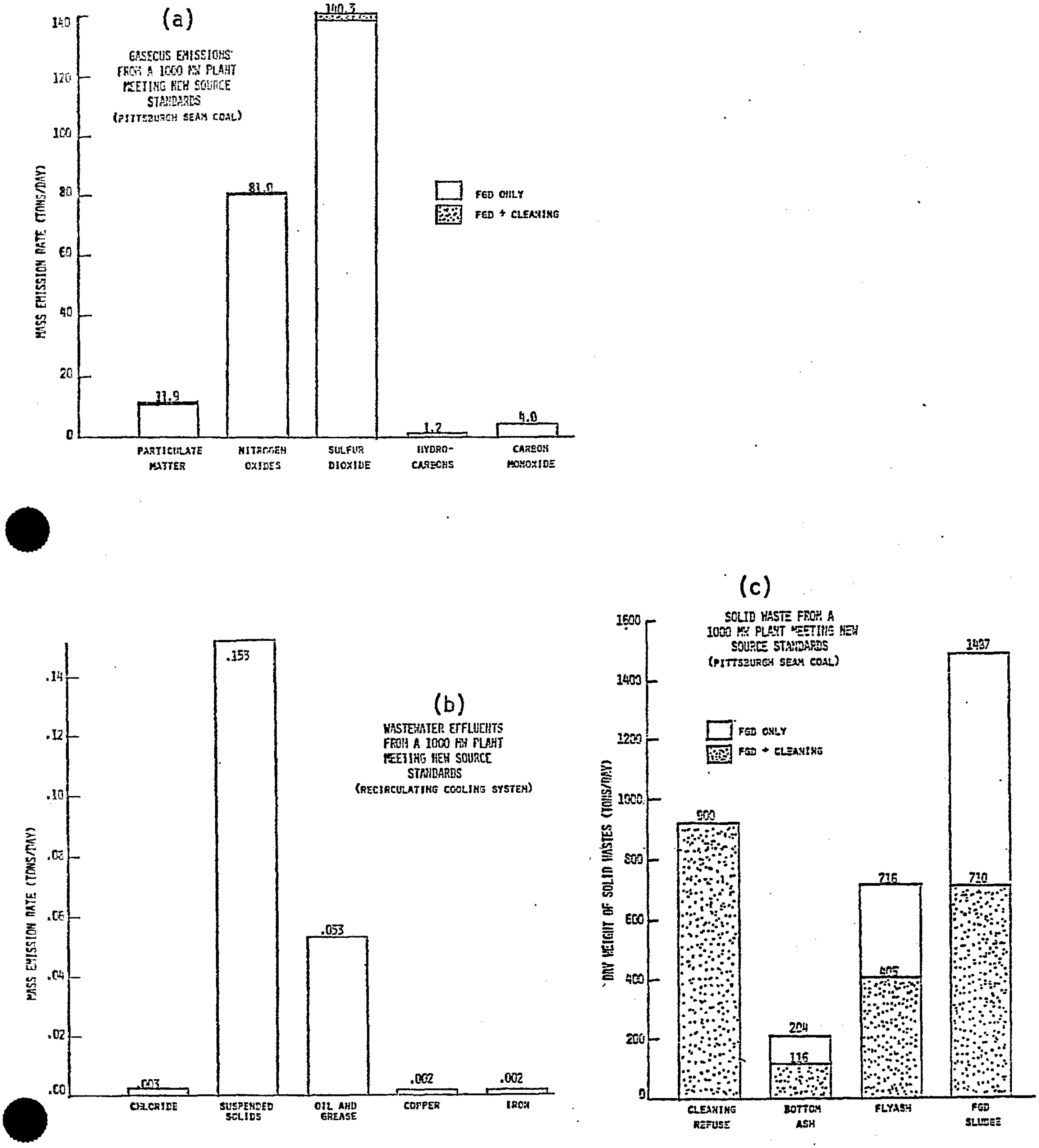


Figure 12. Multimedia pollutant emissions for a plant meeting NSPS levels at 1000 MW net output with Pittsburgh seam coal.

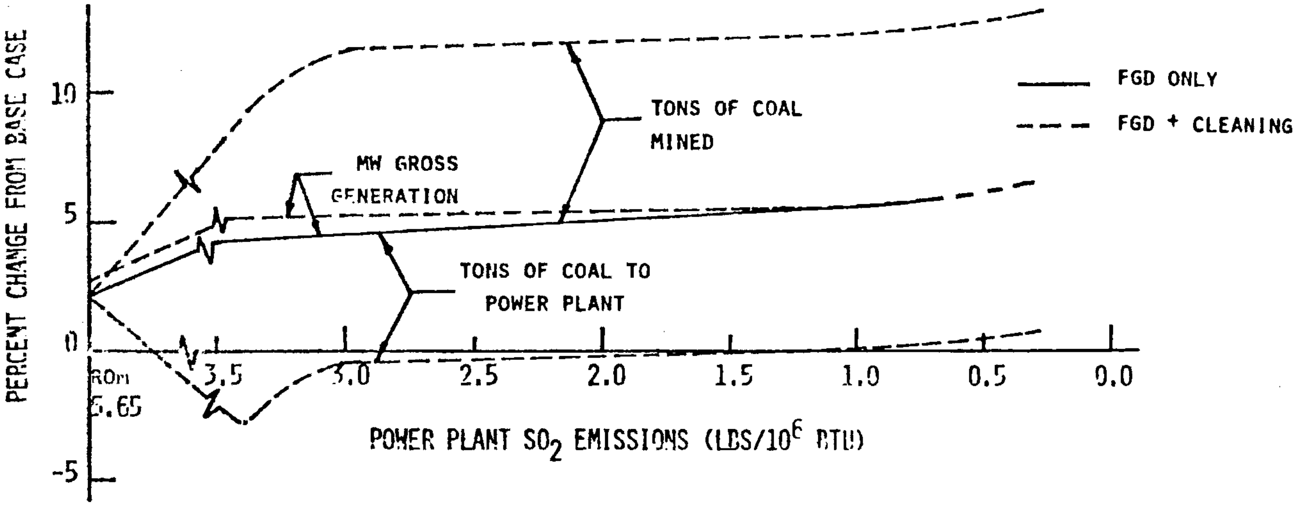


Figure 13. Effect of SO_2 emission standard on coal and power production. (Pittsburgh seam coal)

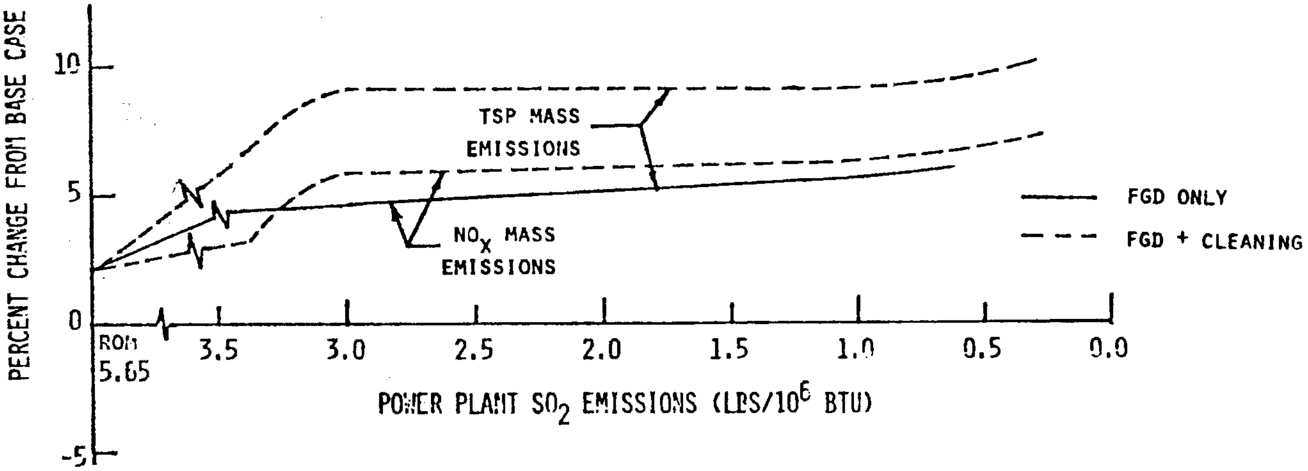


Figure 14. Effect of SO_2 emission standard on TSP and NO_x mass emissions. (Pittsburgh seam coal)

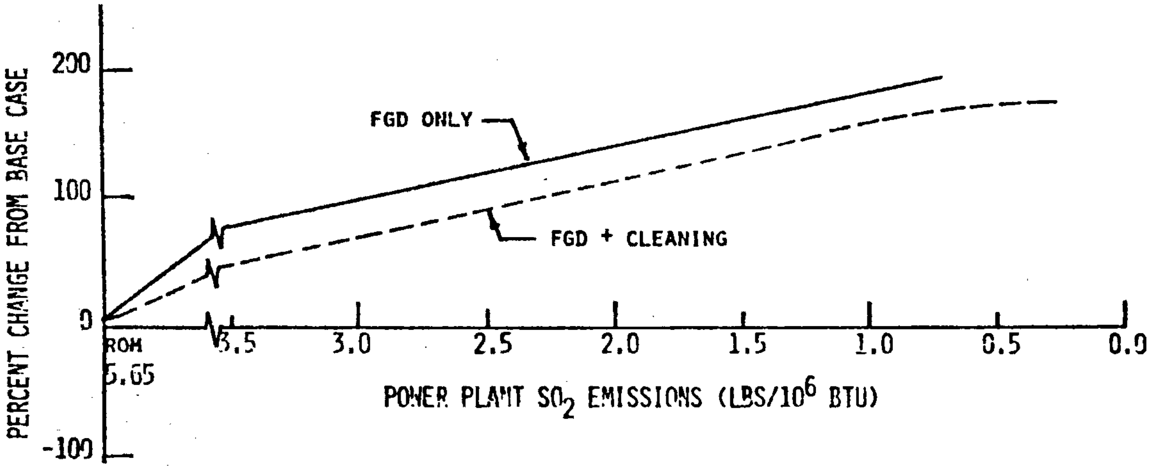


Figure 15. Effect of SO_2 emission standard on total solid waste generation. (Pittsburgh seam coal)

5 percent of the coal energy is lost during the cleaning process. Figure 1 shows how this is reflected in increased coal tonnage that must be mined to maintain the same net power output. Although more coal must be mined using cleaning, the mass of coal delivered to the power plant decreases since washing concentrates the recovered energy in less mass. As the SO_2 regulation becomes more stringent more coal must be fired to maintain the same net power plant output because of the increasing ancillary energy needed for FGD and cleaning plant equipment.

As a result of increased coal demand, particulate (TSP) and nitrogen oxide (NO_x) mass emissions also increase nonlinearly as the SO_2 regulation is tightened (Figure 14). Both TSP and NO_x are assumed to meet the current NSPS levels in all cases. Since these are given in terms of boiler energy input, the absolute mass emission still increases as more coal is fired to the boiler. Figure 15 shows that solid waste generation increases most dramatically as SO_2 emission levels are lowered. In this Figure, solid waste is taken to include the sum of all cleaning plant refuse plus all power plant wastes (principally FGD sludge, flyash, and bottom ash). On a dry basis, the quantity of solid waste increases approximately 180 percent as sulfur emissions are reduced from their uncontrolled value to the NSPS value using this particular coal. This does not include the substantial loss of water that also occurs since cleaning plant and FGD sludge typically contain only 40-50 percent solids by weight.

Interpretation of BACT

Another aspect of SO_2 regulatory policy having cross-media implications concerns the recent Congressional requirement that best available control technology (BACT) be used to reduce power plant sulfur emissions. Two common interpretations of BACT include a fixed emission standard less than the present NSPS (e.g., 0.6 pounds of SO_2 per million Btu), or a constant percent reduction in sulfur (e.g., an 80 percent FGD efficiency, reflecting 90 percent SO_2 removal with 90 percent reliability).[2] Figures 16 and 17 show the impact on dry solid waste and sulfur dioxide mass emissions when these two interpretations of BACT are applied using three eastern coals (from Figure 4), and assuming limestone FGD with and without coal cleaning. Mass emissions are displayed as a function of the fired coal sulfur content expressed as equivalent sulfur dioxide per unit energy input.

One sees that as the input sulfur content decreases, a standard calling for constant removal efficiency results in less SO_2 emissions to the atmosphere as opposed to the fixed emission standard. For the coals modeled here, the lowest sulfur levels are obtained only by cleaning coal prior to combustion. For coals of higher sulfur content the constant FGD removal efficiency yields greater SO_2 emissions than the fixed emission level. This suggests that if an overriding objective of national environmental policy is to minimize sulfur dioxide emissions, regulations should require the more stringent of a constant removal efficiency and fixed emission standard. In such a case, the practical limitations of FGD technology may require higher sulfur coal to be washed prior to combustion. High sulfur coals with no appreciable pyrite content (hence, not subject to washing) could become unusable.

The cross-media impacts associated with BACT were illustrated earlier for one particular coal. Figure 1 shows one effect (on total solid waste generation) for three eastern coals, with and without coal washing. Note that while the combined solid waste of the cleaning and power plants decreases when the high sulfur (Pittsburgh seam) coal is washed before combustion, the reverse is true for the lowest sulfur (Indiana No. VII) coal. Total waste using the median sulfur coal also increases slightly when both FGD and cleaning are used. In all cases more *total* solid waste is generated when washing is used to achieve a given *inlet* SO_2 content. Details of solid waste impacts will vary with the types and washability characteristics of local coals and their geographical relationships to mine and power plant.

Comparison of Conventional and Gasification Combined Cycle Systems

Though the lack of data for operating gasification/combined cycle systems precludes

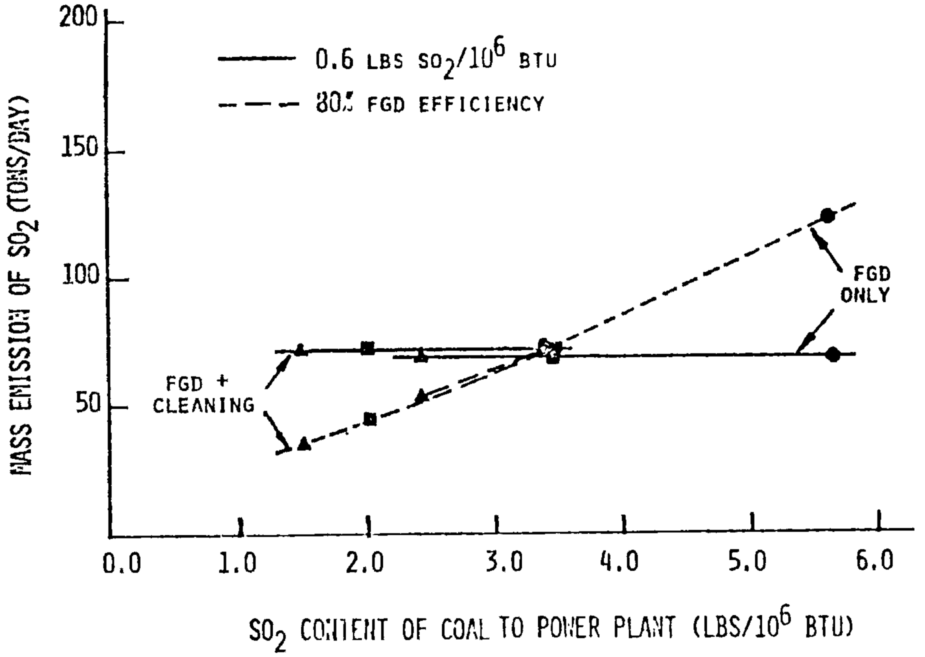


Figure 16. Effect of SO_2 regulation on SO_2 mass emissions for three eastern coals (1000 MW net

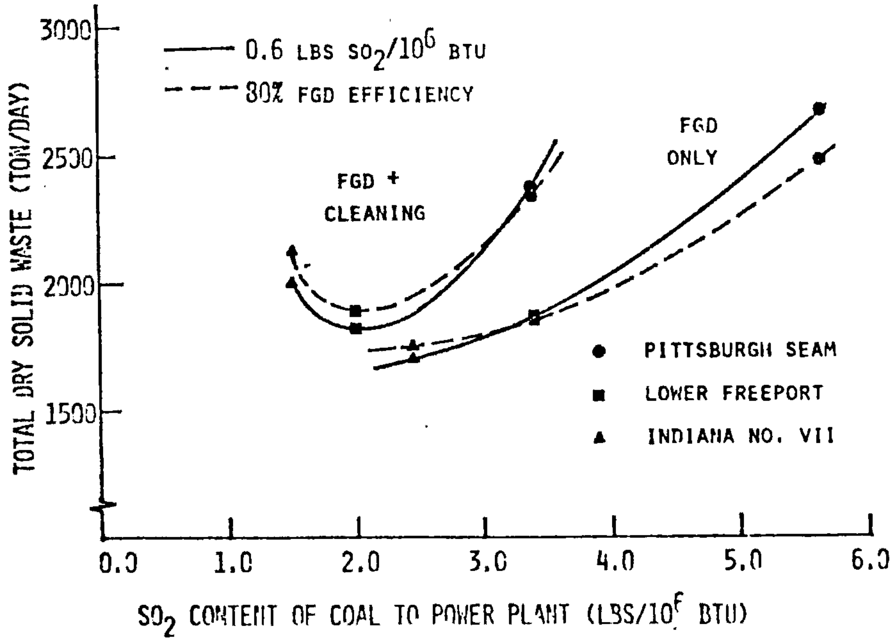


Figure 17. Effect of SO_2 emission regulation on total solid waste generation for three eastern coals (1000 MW net)

rigorous comparisons with a conventional steam-electric plant it is illustrative to examine the environmental consequences implied by typical current designs. Table 9 shows the effect of component energy penalties on the net cycle heat rates for two conventional systems and two gasification system designs. For the gasification system the "best case" design assumes that all steam and electrical requirements needed for desulfurization and wastewater treatment are supplied by recovery or use of waste heat. The "worst case" design assumes that no waste heat can be economically utilized so that all steam and electricity requirements for environmental control systems incur an energy penalty that requires additional coal input to maintain the same net plant output. The wide bounds suggest the

TABLE 9

EFFECT OF SYSTEM ENERGY PENALTIES ON NET CYCLE HEAT RATE FOR A PLANT PRODUCING 1000 MW NET OUTPUT

(Btu per KWH)

(Assuming Pittsburgh Seam Coal and 0.6 lbs $SO_2/10^6$ Btu Coal Input)

System or Component	Conv. Plant w/Limestone FGD	Conv. Plant w/cleaning & FGD	Current Gasification/Comb. Cycle	
			Best Case[a]	Worst Case[b]
Electric Power Generation	8,980	8,980	7,795	8,365
Coal Mining Equipment	55	60	55	75
Coal Preparation:				
Equipment	0	55	95	130
Coal Refuse	0	715	0	0
Primary Coal Pulverizer	25	15	–	–
Coal Gasifier[c]	–	–	2,440	3,175
Flyash Collection	20	20	10	20
Sulfur Removal & Recovery System[d]	345	300	165	1,515
Water Cooling and Treatment[e]	195	190	70	795
Net Cycle Heat Rates:				
Based on coal energy mined	9,620	10,220	10,630	14,075
Based on coal input to plant	9,565	9,505	10,575	14,000
Based on fuel gas from gasifier	n/a	n/a	8,190	11,315

[a] Assumes all energy for desulfurization and wastewater systems is supplied using waste heat.

[b] Assumes all energy for desulfurization and wastewater systems incurs a penalty requiring additional coal input.

[c] Modeled after Bureau of Mines air-blown stirred bed gasifier.

[d] For conventional plant, includes limestone FGD system and its auxiliaries. For gasification plant, includes Benfield acid gas removal, Claus recovery plant and Wellman-Lord tailgas plant.

[e] Includes cooling tower penalty for all Rankine power cycles, plus ammonia recovery, H_2S stripping and biological oxidation for gasification plant.

sizable impact that environmental control system design and performance could have on the viability and environmental impact of gasification-based technologies. If efficient designs can indeed be implemented the overall efficiency of current gasification/combined cycle technologies comes quite close to that of conventional systems (based on coal energy input to the plant). If current designs cannot be realized, gasification is far less efficient than conventional practice. Table 9 suggests that other perspectives of the cycle thermal efficiency are also possible depending on how one chooses to define the "system."

In terms of environmental impact, comparisons between gasification and conventional technologies will depend significantly on future regulatory policy. If coal gasification cycles are subject to the same standards now applicable to direct coal-fired plants the SO_2 mass emissions will depend on the net cycle heat rate (thermal efficiency) based on coal energy input. Figure 18 shows that the current NSPS would result in higher SO_2 emissions using present gasification technology, which is less efficient than conventional technology. Lower emissions would result with future, more efficient designs. On the other hand, if best available control technology must be used, even current gasification processes would achieve lower SO_2 emissions than conventional plants using FGD. TSP emissions would also be virtually eliminated, as it must be to prevent turbine blade erosion. NO_x levels would be less than half current NSPS limits for coal-fired boilers if gas-fired standards could be achieved. However, there is considerable uncertainty about NO_x emissions; they may well be as large or larger than from present coal-fired plants.(9) Finally, less efficient processes will also incur increased coal mining and associated solid waste generation impacts described earlier.

ANALYSIS OF CROSS-MEDIA TRADEOFFS

Given an ability to characterize environmental effluents from different regulatory strategies, the key issue becomes one of defining the levels that are acceptable in light of the tradeoffs that are known to occur. To do this rigorously (Figure 1) requires considerably more knowledge than we have today concerning the transport and transformation of pollutants in the environment and their resulting effects on human health and the ecology. Clearly, more scientific research is needed to provide a stronger basis for policy decisions.

Development of regulations and standards, however, has seldom been hampered by a lack of scientific knowledge. Where data are lacking, personal and societal value judgments play an increasingly important part in public policy. These reflect people's concerns and perceptions regarding levels of environmental risk, economic costs, aesthetic values, political judgments and other concerns that are not often articulated in the development of environmental policy. One aspect of the CMU research on cross-media impacts and tradeoffs concerns the development of methodologies that incorporate both scientific and nonscientific criteria. Two approaches are currently being explored.

Weighted Emissions Inventory

One approach being pursued involves the use of subjective and objective weighting factors for pollutant species and environmental media. This approach was devised by Reiquam, et al., at Battelle Memorial Institute(16) and yields a numerical parameter called the Environmental Degradation Index (EDI). This weighted inventory technique was refined by Dunlap and McMichael at CMU to explicitly display the consequences of alternative values and scientific judgments.(17) The result is a "strategy preference plot," illustrated in Figure 19 for an industrial wastewater control problem. Following the Battelle methodology, the EDI varies with judgments as to the relative importance of air, land, and water as a depository for wastes (reflected by an allocation of 1,000 points). Assumptions regarding the relative damage of pollutant emissions are also incorporated into this methodology. The important point is that when sensitivity analyses are used to explore a wide range of uncertainty in the value of key parameters, the conclusion repeatedly reached for this particular problem is that an intermediate rather than a high level of control is

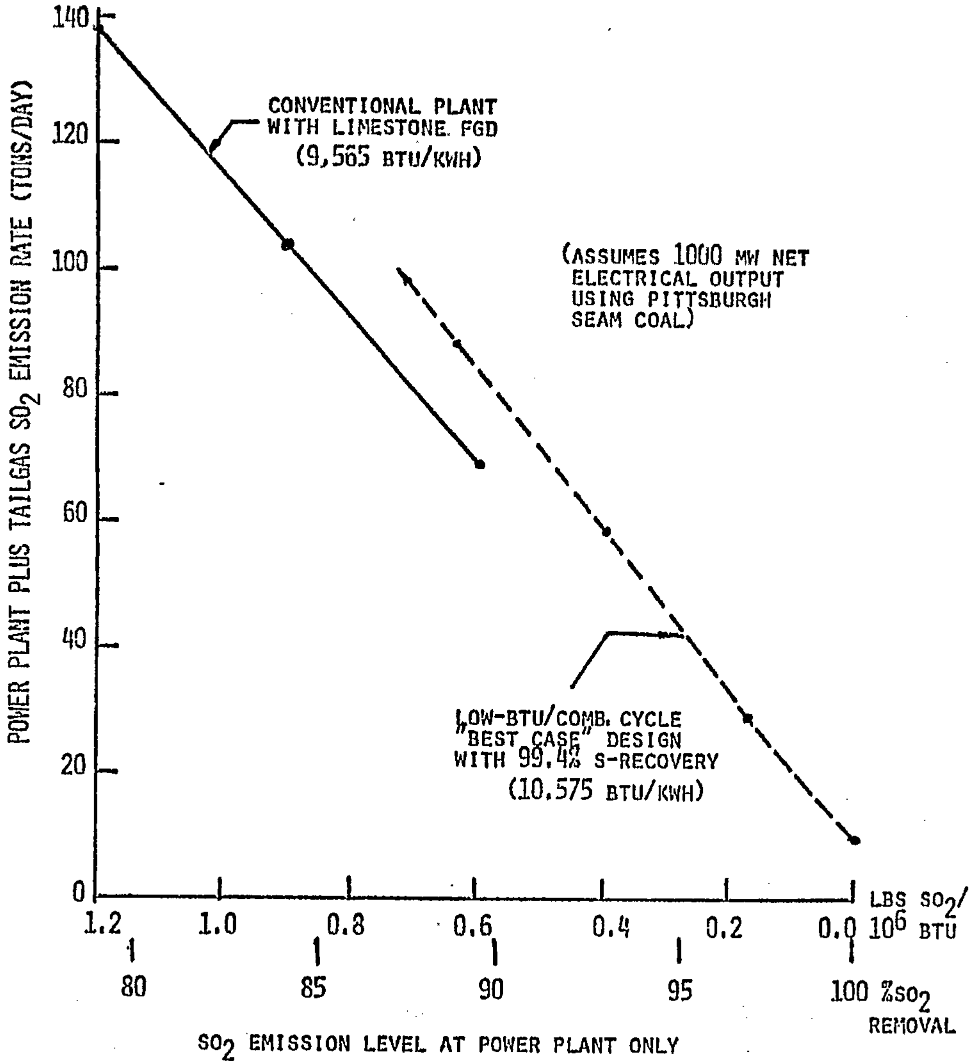


Figure 18. Comparison of SO_2 emissions from present conventional and low Btu/combined cycle plants.

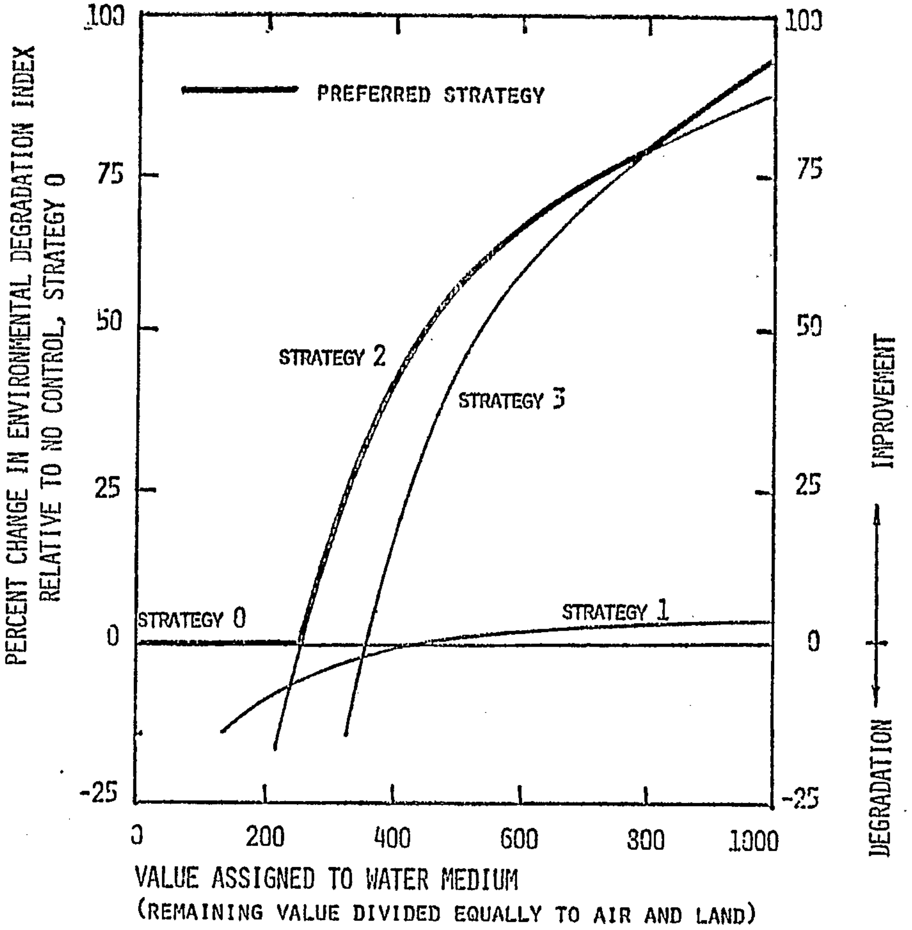


Figure 19. Strategy preference plot for an industrial wastewater problem.

the optimal strategy for minimizing environmental degradation. This is in contrast to current regulatory policy which requires the highest level of control for wastewater constituents, but ignores the substantial negative impacts on other enviornmental media that are introduced. Articulation of such tradeoffs and their relationship to value judgments is an important step in developing regulatory policies that are in the best interests of overall environmental quality.

Multi-Attribute Utility Theory

Recently we have also begun to examine the applicability of multi-attribute utility theory (MAUT) to the cross-media problem. This refers to a quantitative body of theory developed during the past decade that addresses the problem of making decisions to complex problems when there are multiple desirable objectives, all of which are not simultaneously obtainable. Practical applications of this theory have been relatively limited but have proved useful in the identification of policy tradeoffs into other types of problems.(18-20) The application of MAUT to cross-media analysis is in the explicit preference characterization for different levels of selected pollutants reaching different environmental media. To date, such preferences have either been mandated by law (e.g., new source standards and ambient quality standards) or have been decided on a case-by-case basis. Disagreement over preferences have usually revolved around the relative importance of multiple specific goals. In power plant siting issues, for example, there is little disagreement that reduction of adverse environmental impacts is a worthwhile goal; rather, there is disagreement as to how much reduction is appropriate in light of expected adverse impacts and other nonenvironmental considerations.

Multi-attribute utility theory provides a framework which can explicitly describe the values or preferences of different groups or individuals, indicating where and by how much they differ. From this clearer understanding the magnitude of differences can frequently be reduced during further discussions to arrive at optimal decisions. Implementation of MAUT involves a structured interview/questionnaire with ''decision-makers'' from various parties as interest. At CMU, preliminary research has been conducted with representatives of electric utility companies, state environmental control agencies, and local citizen groups treating the cross-media problem in the context of siting a new coal-fired power plant. Focusing on tradeoffs among SO_2, heat and particulates to air, ash and FGD sludge to land, and heat to water, this preliminary work showed that the ''utility functions'' (quantitative value system) of these groups could indeed be characterized using the interview format that was devised. This work remains in progress and will be reported on at a future time.

CONCLUSION

The environmental impact of coal utilization technologies is a complex function of process design, coal properties, and environmental control technology. Regulatory policy for environmental control is a key element in this equation. Historically, regulations and standards limiting the emission of pollutants to air, land, and water have been promulgated without rigorous analysis of the secondary impacts and cross-media effects that adversely influence environmental quality. This paper has described an approach being developed at Carnegie-Mellon University to systematically address such issues as they apply to conventional and advanced technologies producing electricity from coal. Illustrations showed the effect of different SO_2 constraints on the secondary production of pollutants that offset the improvements due to SO_2 reduction alone. Preliminary comparisons of conventional plants and gasification/combined cycle systems were also given. The continuing focus is on careful assessment of the system residuals emitted to various environmental media as a function of process design, coal characteristics, environmental control technology, and environmental regulatory policy. Future efforts will couple this with a cross-media analysis incorporating value judgments and economics to provide greater insight as to the nature of optimal environmental regulatory policy for coal utilization technologies.

ACKNOWLEDGMENTS

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