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A Probabilistic Framework for Environmental Control Cost Estimation

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ABSTRACT

The Integrated Environmental Control (IEC) Model uses Monte-Carlo simulation to perform probabilistic analysis for "study grade" estimates of environmental control costs for coal-fired power plants. This stochastic modeling tool allows the effect of many technical and economic uncertainties to be considered simultaneously. In contrast to traditional sensitivity analysis methods, this provides insight as to the likelihood of different outcomes and the confidence in predicted results. An application of this model is presented comparing an advanced regenerative combined SO₂/NO_x processes, Copper Oxide, to a conventional power plant design using currently available technology. The results show that by-product recovery has a significant influence on the overall cost, and that more stringent solid waste regulations could have a detrimental effect on the economics of advanced processes. The implications of uncertainty analysis for utility planning and R&D management are discussed, along with plans for continued development of the IEC model.

INTRODUCTION

This paper presents results from a new computer model for analyzing alternative pollution control technologies for coal-fired power plants. The Integrated Environmental Control (IEC) model uses a Monte Carlo simulation method to estimate system cost and performance probabilistically. This method of analysis offers a number of advantages over traditional deterministic models, which cannot characterize the effect of variations of many different parameters simultaneously or estimate the likelihood of a particular outcome. The primary aim of the IEC model is to estimate the cost of environmental control systems at a preliminary design level.

Many different performance and cost estimation models are in use by utilities, architects/engineering firms, consultants, and government agencies. These models vary widely in their detail, cost, and complexity depending upon their principal purpose; however, most if not all are deterministic models that report performance and cost as single point values. Sensitivity analysis can then be used to determine the effect of changes in one or two input model values, with all the other values held constant. Spreadsheet programs running on personal computers have greatly facilitated the use of sensitivity analysis, and the display of results in graphical or tabular form. The most important aspect of sensitivity analysis is the ability to identifying factors that are most significant to overall performance and cost.

Some major limitations of sensitivity analysis are the inability to evaluate a large number of case studies or to characterize the expected effect of variations of many different parameters simultaneously. At best, sensi-

tivity analysis provides estimates of upper and lower bounds, provided that "best" and "worst" case parameter values can be identified. Even where this can be done, sensitivity analysis provides no information as to the likelihood of various outcomes, or the probability that one result may be more significant than another.

A PROBABILISTIC MODELING FRAMEWORK

The IEC computer model recently developed at Carnegie Mellon University with support from the U.S. Department of Energy (DOE) (Rubin et al., 1986), allows integrated environmental control systems to be easily configured and analyzed. The term "integrated environmental control" includes combinations of pre-combustion, combustion and post-combustion methods of pollution abatement. A multi-media approach to pollution control, considering the interactions among gaseous, liquid and solid waste control options, and the notion of combining separate pollution control processes to achieve simultaneous removal of two or more pollutants in a single operation, also are part of this concept.

The IEC model currently can simulate the performance of systems involving combinations of 15 conventional and advanced air pollution control processes (Figure 1).¹ The options at the top of Figure 1 represent currently available technologies, while those below the dashed line represent several new processes being developed with DOE support. Capital and annualized costs are estimated, along with system process design and performance characteristics. The model contains roughly 500 independent parameters reflecting site-specific plant and fuel parameters, as well as key economic, regulatory and process design variables. Details are provided in Rubin et al. (1986).

As mentioned previously, the IEC model uses Monte Carlo simulation in which probability distribution functions are assigned to various performance and economic input parameters. Then, random samples are repeatedly taken from these distributions to calculate derived quantities. This yields an overall distribution function of the performance or cost results of the model, which characterizes the likelihood of a result exceeding a specified value, or lying within some specified range. Anywhere from several

¹ The primary units in this paper are English units which are prevalent in this industry. To convert to SI units, use the following conversion factors:

1 acfm = 4.719x10 ⁻⁴ m ³ /s (actual)	1 ft ³ = 0.0283 m ³
1 acre = 0.405 hectare	1 inch = 0.0254 m
1 Btu/kWh = 1.054 kJ/kWh	1 lb = 0.454 kg
1 Btu/lb = 2.324 kJ/kg	1 lb/10 ⁶ Btu = 430 ng/J (g/10 ⁶ kJ)
°F = 1.8°K - 459.67	1 ton = 0.9074 metric
1 ft ² = 0.0929 m ²	

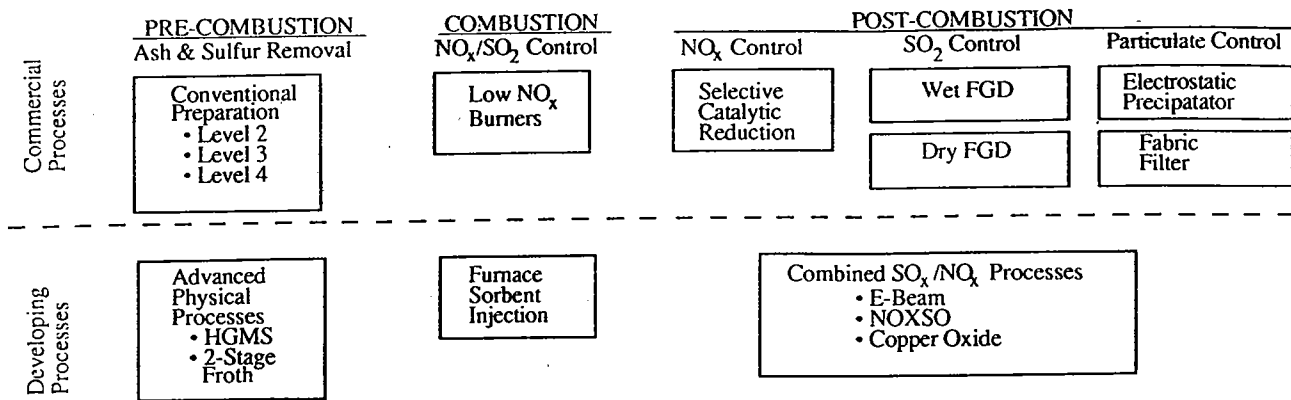


FIG 1. Selected Air Pollution Control Options for Pulverized Coal-Fired Boilers

dozen to several hundred samples of the probability distributions may be required in a simulation, depending upon the size and complexity of the model, and the level of confidence desired.

A unique feature of the IEC model is the use of the DEMOS software system developed by Henrion and his co-workers to facilitate the analysis of uncertainty (Henrion and Nair, 1987). Figure 2 shows some of the ways such uncertainty may be expressed. A normal (Gaussian) distribution (Figure 2a) reflects a symmetric but varying probability of a parameter value being above or below its nominal (mean) value. A characteristic of this distribution is the standard deviation, σ . The properties of a Gaussian distribution are such that there is a 68% probability that a value lies within 1σ of the mean and a 95% probability of it being within 2σ of the mean. In contrast, for a uniform distribution (Figure 2b) there is an equal likelihood of a value lying anywhere within a specified range. A lognormal distribution, on the other hand, is skewed such that there is a higher probability of values lying on one side of the median than the other (Figure 2c). User-specified distributions of uncertainty also may be employed by assigning probabilities to discrete values or to various fractiles across a range (Figure 2d). Of course, for a particular set of assumptions the model also can produce deterministic results.

TECHNICAL DESCRIPTION

Advanced IEC design concepts employ new processes to achieve high levels of sulfur dioxide, nitrogen oxide, and particulate emissions control. A "conventional" power plant design -- to which IEC systems are compared -- is assumed to employ a selective catalytic reduction (SCR) system for NO_x control, a cold-side electrostatic precipitator (ESP) for particulate removal, and a wet limestone flue gas desulfurization (FGD) system for SO₂ control when using high-sulfur coal. For low sulfur coals, the conventional system would employ a lime spray dryer for SO₂ removal, with the dry FGD system located upstream of a fabric filter particulate collector. In either case, the potential for additional pre-combustion pollutant removal through conventional or advanced coal cleaning also is part of the modeling framework.

Baseline Plant Design

Table I summarizes some of the key design constraints assumed for the analysis. We model a new power plant burning a high sulfur midwestern coal (Table II), with the option of washing the coal to achieve additional sulfur and ash removal in a conventional coal preparation plant. The assumed emission constraints for particulate and SO₂ emissions are the current federal New Sources Performance Standards (NSPS), which allow credit for sulfur removal through coal cleaning prior to combustion (Rubin et al., 1986). The assumed NO_x emission limit, however, is nearly an order of magnitude below the current NSPS value, reflecting levels now required for coal-fired power plants in Germany and Japan (OECD, 1987). This level of NO_x emissions also is being achieved at a first generation coal gasification combined cycle power plant in the U.S. (Rubin, 1987).

To meet environmental regulations, the pulverized coal-fired plant is assumed to use a conventional wet limestone FGD system with forced oxidation for SO₂ control, a cold-side electrostatic precipitator (ESP) for particulate control, and a "high dust" SCR system plus low-NO_x burners for

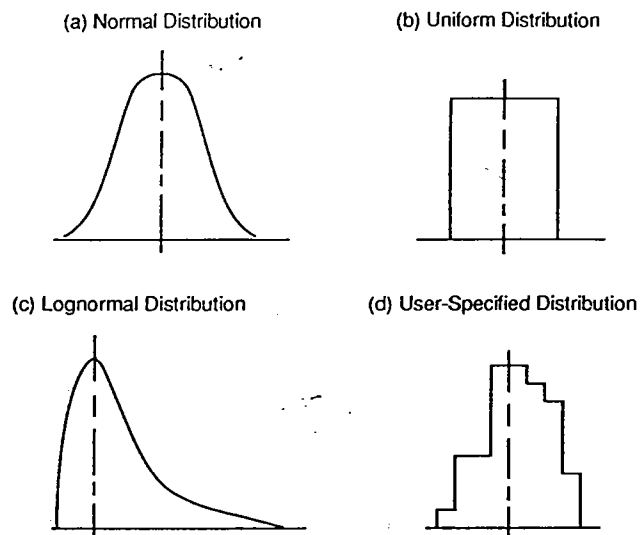


FIG 2. Some Ways of Expressing Uncertainty

NO_x control. Nominal design characteristics for these systems are summarized in Table III, along with the uncertainty ascribed to selected model parameters in this analysis.

The principal uncertainties deal with design aspects of the FGD and SCR systems. For the wet FGD system, probabilities were assigned to three technical innovations currently found in Japanese and European designs, which could reduce the cost of conventional U.S. systems in the coming decade. Relatively high probabilities were assigned to eliminating spare scrubber trains (absorber vessels) and stack gas reheat (though with an additional capital cost for improved stack liners). A lower probability was assumed for designs using smaller numbers of larger absorber vessels in lieu of the multiple train configurations used in U.S. designs today. The probabilities assigned reflect the judgment of the authors as well as several other U.S. experts (EPRI, 1988).

For the SCR system, key uncertainties are the lifetime and cost of the SCR catalyst in U.S. plants burning high sulfur coal. The assumed probability distribution for SCR catalyst lifetime (Table III) reflects a belief that current Japanese and German experience with SCR on low sulfur coals will not be directly applicable to high sulfur U.S. coal plants because of a greater potential for catalyst poisoning (EPRI, 1988; Cichanowicz and Offen, 1987). Accordingly, lifetime assumptions for the stochastic analyses are skewed toward shorter durations relative to the nominal lifetime of 2.6 years based on recent German experience (ECE, 1986).² SCR catalyst

² This assumes a 65 percent capacity factor for U.S. plant operations. The SCR system model expresses lifetime in terms of the hours of operation for replacement of a catalyst layer. The nominal value for this parameter is 5,000 hours at full capacity for a three-layer reactor design, or 15,000 hours total.

TABLE I
Selected Input Parameter Assumptions for Case Studies

Model Parameter	Nominal Value	Uncertainty Distribution	Values (or σ as % of mean)
Emission Constraints			
Nitrogen Oxides	0.08 lbs/MBtu		
Sulfur Dioxide	90% Removal		
Particulates	0.03 lbs/MBtu		
Power Plant Parameters			
Gross Capacity	522 MW		
Gross Heat Rate	9500 Btu/kWh	-1/2 Normal	(1.8%)
Capacity Factor	65%	Normal	(7%)
Excess Air (boiler/total)	20% / 39%	Normal	(2.5%)
Ash to Flue Gas	80%		
Sulfur to Flue Gas	97.5%		
Preheater Inlet Temp	700 °F		
Preheater Outlet Temp	300 °F		
Financial Parameters			
Inflation Rate	0%		
Debt Fraction / Real Return	50% / 4.6%		
Com. Stock Frac / Real Return	35% / 8.7%		
Pref. Stock Frac / Real Return	15% / 5.2%		
Federal Tax Rate	36.7%		
State Tax Rate	2.0%		
Ad Valorem Rate	2.0%		
Investment Tax Credit	0%		
Book Life	30 years		
Real Escalation Rates	0%		
Real Discount Rate (calc)	6.13%		
Fixed Charge Factor (calc)	10.34%	Uniform	7.24 - 13.44%
Levelization Factors	1.000	Normal	(3%)

TABLE II
Properties of Illinois No.6 Coal Used for Case Studies
(As-Fired Basis)

Coal Property	Run-of-Mine Coal	Washed Coal ^a
Btu/lb	10,190	10,330
% S	4.4	3.1
% C	57.0	57.7
% H	3.7	4.0
% O	7.2	8.4
% N	1.1	1.1
% Ash	14.4	8.2
% Moisture	12.3	17.5
\$/ton (at mine)	28.10	32.70
\$/ton (transport)	5.90	5.90

^a Model results for a 30% sulfur reduction (normalized on coal energy content) using conventional coal cleaning (Level 3 plant design).

cost is assumed to be slightly higher than current costs in West Germany, which are nearly 50 percent below the price several years ago when German catalysts were imported exclusively from Japan (ECE, 1986). Currently, several firms including one U.S. company offer SCR catalyst in Germany; the presumption is that suppliers would be equally competitive in a mature U.S. market. Uncertainty in future catalyst cost thus is assumed to be normally distributed, reflecting a potential for either higher or lower prices depending on market circumstances and innovations stemming from current catalyst research.

Given that SCR systems are not yet commercially operating in the U.S., and that a number of new problems are anticipated in high sulfur coal applications, we take a conservative view of the total system capital cost as reflected by the assumed probability distribution indicated in Table III. Significantly higher costs might be associated with the SCR reactor design, with modifications to the air preheater needed to deal with potential problems of sulfate aerosols formed in the catalyst bed and/or with other aspects of process integration (Cichanowicz and Offen, 1987). On the other hand, we also include a smaller probability of capital costs being reduced slightly as a result of experience gained during early commercializations.

TABLE III
Nominal Parameter Values and Uncertainties for the Conventional Environmental Control System

Model Parameter	Nominal Value ^a	Uncertainty Distribution	Value (or σ as % of mean) ^b
SCR Process			
Space Velocity	2850 hr ⁻¹ (calc)	Normal	(10%)
NH ₃ Stoichiometry	0.99 (calc)	Normal	(2.5%)
Catalyst Life	15,000 hrs	Chance	5% @ 1,275 hrs; 30% @ 5,700 hrs; 50% @ 11,400 hrs; 14% @ 17,100 hrs; 1% @ 28,500 hrs
Energy Requirement	(calc)	Normal	(10%)
Ammonia Cost	\$150/ton	Uniform	\$150 - 225/ton
Catalyst Cost	\$460/ft ³	Normal	(7.5%)
Direct Capital Cost	(calc)	Triangular	0.8x, x, 2x
Operating Cost (excl. Cat.)	(calc)	Normal	(15%)
Cold-Side ESP			
Specific Collection Area	(calc)	Normal	(5%)
Energy Requirement	(calc)	Normal	(10%)
Total Capital Cost	(calc)	Normal	(10%)
Operating Cost	(calc)	Normal	(10%)
Wet FGD System			
Molar Stoichiometry	1.12 (calc)	Normal	(2.5%)
No. Operating Trains	4 (calc)	Chance	10% @ 1; 20% @ 2; 40% @ 3; 30% @ 4
No. Spare Trains	1 (calc)	Chance	65% @ 0; 35% @ 1
Reheat Energy	(calc)	Chance	75% @ 0; 25% @ x
Total Energy Use	(calc)	Normal	(10%)
Limestone Cost	\$15/ton	Uniform	\$10 - 15/ton
Direct Capital Costs	(calc)	Normal	(10%)
Operating Costs	(calc)	Normal	(10%)
Solid Waste Disposal			
Land Cost	\$6,500/acre	Normal	(15%)
Direct Cost	(calc)	Normal	(15%)
Operating Cost	(calc)	Normal	(15%)

^a Values for selected parameters calculated within the model are shown for convenience, along with values of user-specified parameters.

^b For uniform distributions actual values are shown. For triangular distributions, endpoints and median are shown.

Advanced Process Design

One advanced plant design concept combines SO₂ and NO_x removal in a single step using the fluidized bed copper oxide process, shown in Figure 3 (Drummond, 1986). In the fluidized bed absorber, NO_x is reduced to nitrogen through the addition of ammonia, while SO₂ is absorbed onto pellets impregnated with copper oxide. The sorbent is then regenerated, with sulfur recovered as by-product sulfuric acid. Plant solid waste thus consists only of fly ash collected in a conventional baghouse.

Figure 4 shows the performance data obtained by DOE/PETC for three different bed heights in a small-scale unit.³ Also shown are the regression curves derived to model the process performance; similar curves were developed for NO_x removal (Rubin, et al., 1986). Key issues in the scale-up and economics of this process include the required stoichiometric ratio of copper-to-sulfur, the rate of sorbent attrition, the ease of sorbent regeneration, and the production and sale of by-product acid or sulfur.

The reactions occurring in the absorber are highly exothermic and raise the temperature of the flue gas significantly for high sulfur coals. The absorber is located upstream of the air-preheater. Previous studies (Frey, 1987) have indicated that building a larger air preheater to capture more of the energy released by the absorber decreases the overall levelized system cost for high sulfur coals. If the air preheater size is not increased, the higher flue gas temperature would increase the capital and operating cost of

³ The process is currently being scaled up to a 1 MW pilot plant to be tested on a slip stream of a power plant in Illinois.

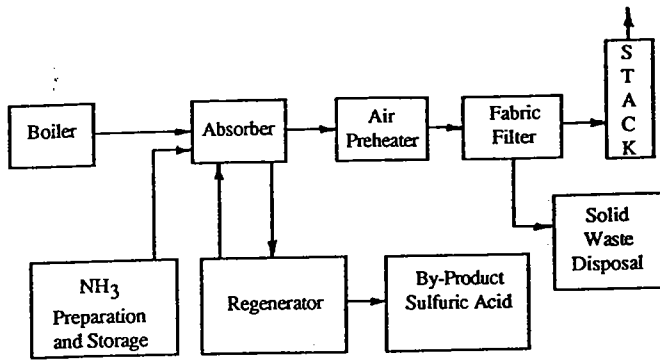


FIG. 3 Advanced Plant Design with DOE Copper Oxide Process

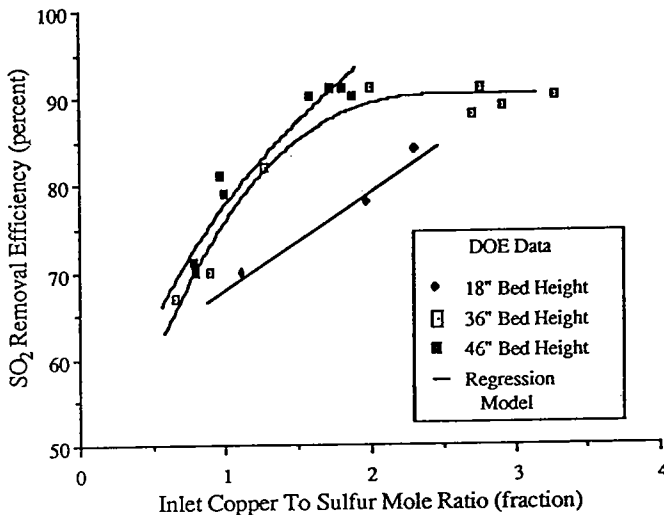


FIG. 4. SO₂ Removal Efficiency Versus Copper-to-Sulfur Ratio for the DOE Copper Oxide Process

particulate control devices located downstream of the air preheater. The benefit of a larger preheater, however, decreases as the sulfur content decreases. The performance and interactions among all of these components were explicitly modeled in this analysis.

Nominal values of key process parameters for the copper oxide processes are summarized in Table IV along with the uncertainties that were assumed. Higher probabilities were assigned to cost increases than to cost decreases in a number of key areas (e.g., by-product credits, regeneration costs, and ammonia costs). The interaction between cost and process performance parameters, however, is captured by the analytical model.

Overall, a number of potential process design improvements, particularly the elimination of redundant trains, lower attrition rates, and a lower cost of copper oxide pellets, may significantly reduce both the capital and operating costs of this process relative to the nominal (deterministic) assumptions. A contingency cost factor is nonetheless included in the capital cost breakdown to reflect the increased expenses expected in a full-scale plant design (Rubin et al., 1986).

The sulfur recovery process of a regenerative air pollution control technology has a major impact on economics, although such effects have not yet been widely studied for advanced SO₂/NO_x systems. A contact sulfuric acid plant is used as the sulfur recovery system for the copper oxide process. The process of recovering sulfuric acid in a contact sulfuric acid plant involves cooling and drying the inlet gas, converting sulfur dioxide to sulfur trioxide, and finally absorbing the sulfur trioxide in sulfuric acid. These plants are commercially available and very reliable, but their costs can vary greatly depending upon the characteristics of the inlet gas stream.

Copper Oxide usually is a net producer of energy for high sulfur coals. This energy comes from two sources: the exothermic reactions in the absorber, and those in the sulfuric acid plant. The reactions in the absorber raise the temperature of the flue gas. This additional energy can be capture

TABLE IV
Nominal Parameter Values and Uncertainties for the Advanced Environmental Control System

Model Parameter	Nominal Value ^a	Uncertainty Distribution	Value (or σ as % of mean) ^b
Copper Oxide Process			
Molar Cu/S Ratio	2.4 (calc)	Normal	(10%)
Sorbent Attrition Rate	0.06%	Normal	(41%)
Ammonia Stoichiometry	0.91 (calc)	Normal	(6.25%)
Regeneration Temp	900 °F	Normal	(2%)
No. Operating Trains	4 (calc)	Chance	{ 10% @ 1; 20% @ 2; 40% @ 3; 30% @ 4
No. Spare Trains	1 (calc)	Chance	{ 50% @ 0; 50% @ 1
Sorbent Cost	\$5.00/lb	-1/2 Normal	(25%)
Methane Cost	\$4.50/MCF	Triangular	\$3.375, 4.50, 6.75/MCF
Ammonia Cost	\$150/ton	Uniform	\$150 - 225/ton
Sulfur Acid Cost	\$50/ton	-1/2 Normal	(10%)
Total Capital Cost	(calc)	Normal	(10%)
Fabric Filter			
Air-To-Cloth Ratio	2.0 acfm/ft ²	-1/2 Normal	(10%)
Bag Life	2 yrs (calc)	Normal	(25%)
Energy Requirement	(calc)	Normal	(10%)
Bag Cost	\$0.80/ft ²	Normal	(5%)
Operating Cost	(calc)	Normal	(15%)
Total Capital Cost	(calc)	Normal	(15%)
Solid Waste Disposal			
Land Cost	\$6,500/acre	Normal	(15%)
Direct Capital Cost	(calc)	Normal	(15%)
Operating Cost	(calc)	Normal	(15%)

^a Values for selected parameters calculated within the model are shown for convenience, along with values of user-specified parameters.

^b For uniform distributions actual values are shown. For triangular distributions, endpoints and median are shown.

in the air preheater to raise the inlet temperature of combustion air to the boiler. A 100°F increase in combustion air results in approximately a 2% fuel saving (Babcock & Wilcox, 1978). The energy from the acid plant is usually in the form of superheated steam. Energy from both the absorber and the acid plant can be used to generate additional electricity, but converting heat energy to electricity requires equipment, i.e. boilers, steam turbines, pumps, and generators. The IEC model accounts for the energy produced as a fuel credit and increases the size of the base power plant to cover the capital and operating costs associated with converting this energy to electricity.

Other Uncertain Factors

Combined pre- and post-combustion control processes can play a significant role in reducing the capital and operating costs of a power plant. In this analysis, a physical coal cleaning plant model was used to estimate the characteristics and cost of cleaning the raw coal to various levels of sulfur reduction (Rubin et al. 1986). Coal transportation costs were assumed to remain constant in computing the delivered price of coal. Table V shows the input parameters associated with the coal preparation plant.

In addition to uncertainties in environmental control system design and cost parameters, additional uncertainties were included in selected power plant characteristics and economic/financial factors that affect overall cost comparisons. Table I summarizes these parameters and the uncertainties that were assumed. Variations in the annual average capacity factor were assigned a normal (Gaussian) distribution encompassing values between approximately 50 and 80 percent. Heat rate uncertainties for the base plant were assumed to be skewed in the direction of performance improvements over the next decade. Uncertainty also was ascribed to the fixed charge rate, which was assumed to lie anywhere within plus or minus 30 percent of the nominal value with a uniform probability.⁴ Finally, the con-

⁴ This assumption reflects uncertainty in the various factors that constitute the fixed charge rate, principally the real rates of interest, debt, and taxes (EPRI, 1987).

TABLE V
Nominal Parameter Values and Uncertainties for the Coal Preparation Plant

Model Parameter	Nominal Value	Uncertainty Distribution	Value (or σ as % of mean)
Preparation Plant Parameters			
Cleaned Coal Output	500 dry tons/hr		
Annual Operating Hours	3,325 hrs/yr		
Coarse Screen Sizes	1.5" x 0.375"		
Mid Screen Sizes	0.375" x 14 mesh		
Fine Screen Sizes	14 mesh x 0		
Prob Error (Coarse/Mid/Fine)	0.035 / 0.03 / 0.09		
Surf Moist (Coarse/Mid/Fine)	4% / 8% / 20%		
Economic/Financial Parameters			
Inflation Rate	0%		
Real Discount Rate	12%		
Plant Life	20 years		
Capital Recovery Factor	13.4%		
Operating Cost Factors	(Rubin, et al., 1986)		
Total Capital Cost	(calc)	Normal	(15%)
Total Operating Cost	(calc)	Normal	(15%)

stant dollar levelization factor applied to annual operating costs was assumed to be normally distributed, reflecting the potential for either positive or negative real cost escalation rates over the lifetime of the plant. No uncertainties were ascribed to coal characteristics for this analysis since alternative coals were being modeled explicitly; however, such variability could be included in the modeling framework if desired.

ECONOMIC COMPARISON

An objective of this paper is to show how a probabilistic evaluation framework can be used to obtain new insights in comparing advanced process for combined SO₂/NO_x removal with conventional technology represented by SCR in combination with FGD. First, a baseline plant configuration is defined along with nominal values of plant, fuel, and process design parameters. Then, uncertainties are ascribed to key parameters affecting system cost. The objective of the analysis is to compare the likely costs of conventional and advanced systems that might be deployed commercially a decade or so from now.

Deterministic Results

Figures 5-7 show the effect of integrated system designs employing coal cleaning in conjunction with post-combustion environmental control. Higher delivered coal prices associated with sulfur and ash removal from physical coal-cleaning (Figure 5) are offset by reductions in the cost of environmental control equipment at the power plant (Figure 6). The net effect on the annualized cost of pollution control (Figure 7) is a decrease in the cost of the fluidized bed copper oxide process up to a level of 25 percent sulfur removal via coal cleaning. For the conventional plant, coal cleaning has a negligible to slightly negative impact on overall cost for all levels of coal washing.

Coal Sulfur Effects. Deterministic results for the run-of-mine coal and optimal coal washing levels are shown in Table VI. For the nominal cost and performance assumptions, the copper oxide process has a slightly lower capital cost than the conventional plant for the case with unwashed coal. When combined with coal washing, however, the capital cost is 30 percent below that of the baseline power plant. The levelized annual cost of the copper oxide system is nine percent higher than the conventional plant without coal cleaning, but 18 percent cheaper when combined with pre-combustion controls. The cost savings from coal cleaning come primarily from the lower sulfur content. Thus, coal sulfur content is important to the viability of the copper oxide process as an advanced system for simultaneous SO₂/NO_x control.

Air Preheater Effects. Table VII shows the benefit of installing a larger air preheater for the Copper Oxide process. The Copper Oxide process produces a significant amount of heat energy with high sulfur coals. If the air preheater size remains unchanged some of the additional energy will

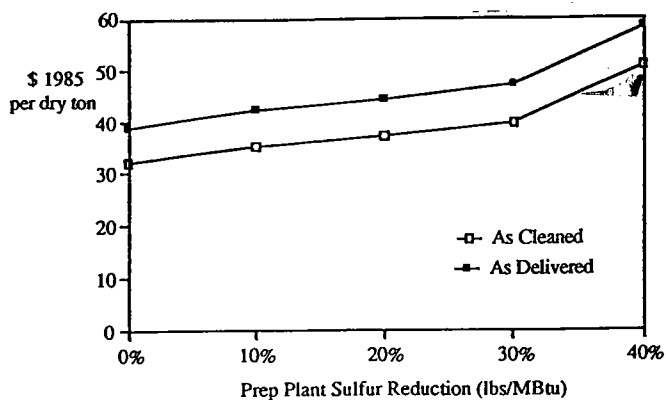


FIG 5. Coal Price Versus Sulfur Reduction from Coal Cleaning (Dry Basis)

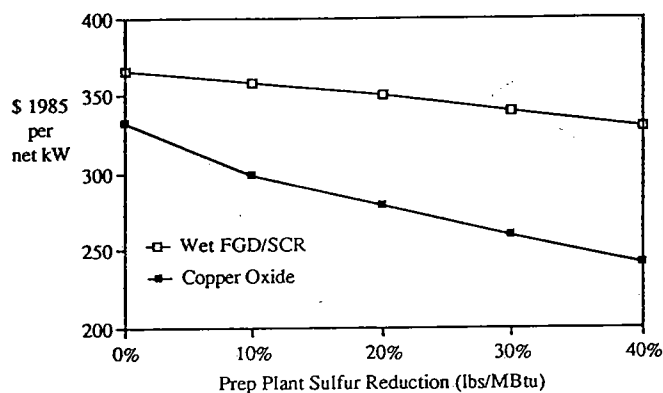


FIG 6. Pollution Control Capital Cost Versus Sulfur Reduction from Coal Cleaning

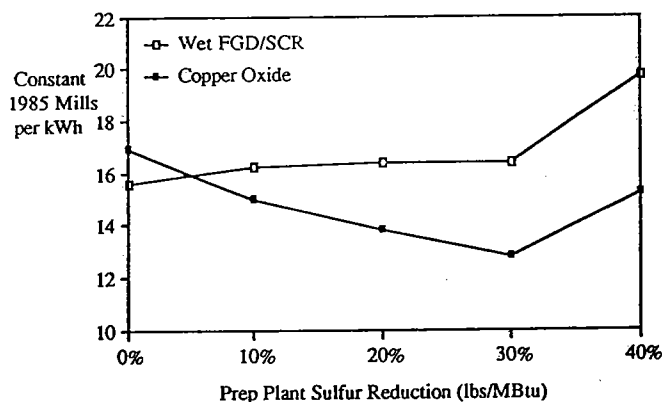


FIG 7. Levelized Pollution Control Cost Versus Sulfur Reduction from Coal Cleaning

be captured; however, the temperature of the flue gas leaving the air preheater will still be higher. This raises the actual volumetric flow rate of gas, which drives up the capital and operating cost of the fabric filter. If an air preheater large enough to maintain the same exit temperature of 300°F is installed, the fuel credit increases from by a factor of two. The additional capital for the larger air preheater is \$34/kW for the raw coal and \$18/kW for the washed coal. However, the fabric filter capital costs decrease by \$7/kW and \$4/kW, respectively, along with decreases in annual operating costs. The net effect of increasing the preheater size is a 0.13 mills/kWh savings in levelized annual cost using a high sulfur coal (Table VII).

TABLE VI
Summary of Total Pollution Control Costs
for Wet FGD/SCR and Copper Oxide Processes
(4.4% S Illinois No. 6 Coal)
(All Costs in Constant 1985 Dollars)

Process Configuration	No Coal Cleaning		Optimal Coal Cleaning ^a	
	Capital \$/net kW	Levelized Mills/kWh	Capital \$/net kW	Levelized Mills/kWh
Conventional Plant Design				
Coal Cleaning	-	-	(6) ^b	1.9
SCR System	69	3.7	70	3.7
Cold-Side ESP	43	0.9	40	0.8
Wet FGD System	197	9.0	192	8.3
Solid Waste Disposal	56	2.0	43	1.6
Total	365	15.6	339	16.3
Advanced Plant Design				
Coal Cleaning	-	-	(3) ^b	1.9
Copper Oxide Process	244	14.4	180	8.5
Fabric Filter	62	1.4	62	1.4
Solid Waste Disposal	25	1.1	21	1.0
Total	332	16.9	260	12.8

^a 30% sulfur reduction on lbs/MBtu basis.

^b These costs (or credits) result from changes in the base plant cost.

TABLE VII
Summary of Component Effects on Copper Oxide Process Cost
(4.4% S Illinois No. 6 Coal)
(Added Costs in Constant 1985 Dollars)

Process Component	No Coal Cleaning		Optimal Coal Cleaning	
	Capital \$/net kW	Levelized Mills/kWh	Capital \$/net kW	Levelized Mills/kWh
Larger Air Preheater ^a	27	-0.13	14	-0.06
Acid Plant ^b	33	-1.44	25	-0.85
Waste Disposal ^c	22	1.03	8	0.42

^a This is the difference in total pollution control cost between using the original size air preheater and building a larger air preheater (including fuel credits). The larger air preheater is assumed for the nominal plant design.

^b This includes the net effects of power consumption, steam generation, acid plant costs and the sale of sulfuric acid at \$50/ton.

^c This is the effect on total pollution control costs if the direct capital and operating cost of waste disposal were increased by the factor, $(1 + S/S_0)$, where S is the mass flow rate of sorbent in the waste stream, and S_0 is the mass flow rate of sorbent when burning the unwashed coal.

By-Product Recovery Effects. The importance of the sulfur recovery system to overall plant economics is shown in Table VII. As can be seen, the acid plant has a very significant effect on the overall costs. The acid plant for process this configuration consumes a significant amount of energy, 1.7 MW, while producing a small amount of steam, about 0.5 MW equivalent. On a levelized cost per ton of acid basis, it costs about \$24/ton using unwashed coal. However, if the acid is sold at \$50/ton, the profit of \$26/ton generates \$4 million in annual revenues.

Potential Hazardous Waste Effects. While high-volume wastes from power plants are currently exempted as a hazardous waste under the Refuse Conservation and Recovery Act (RCRA), there is concern that some chemicals emitted by power plants may be classified as hazardous or toxic wastes in the future (Chow and Morasky, 1987). Waste from the Copper Oxide process may be susceptible of such classification, since approximately 1% of the waste is metal in the form of copper oxide, copper sulfate, or alumina substrate. Since it is unknown what future regulations will exist and exactly how they would affect the Copper Oxide process, a simple algorithm was developed which increased the capital and operating cost of waste disposal in proportion to the attrition rate of sorbent lost to the particulate waste stream. The formula is, $\$_0 * (1 + S/S_0)$, where $\$_0$ is the nominal

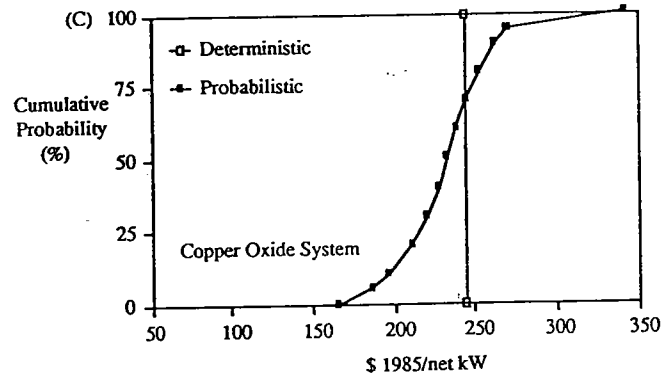
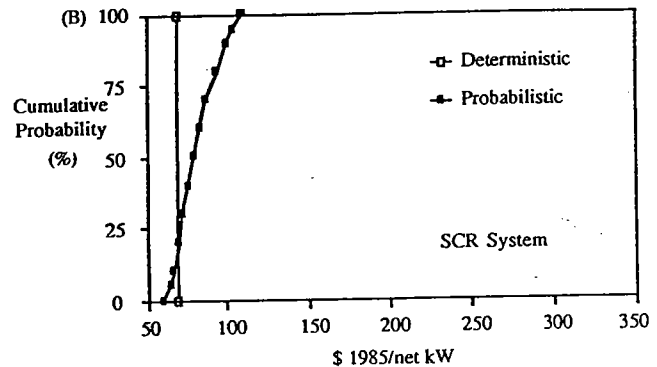
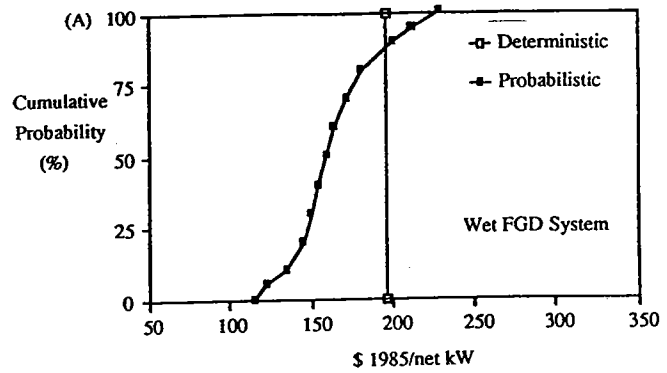


FIG 8. Probabilistic vs. Deterministic Results for Capital Cost for Selected Components

capital or operating cost for waste disposal, S is the mass flow rate of sorbent in the waste stream, and S_0 is the mass flow rate of sorbent when burning the unwashed coal. This equation doubles the capital and operating cost of waste disposal for the raw coal; however, as the flow rate decreases with coal washing, the cost decrease. Table VII shows that increased waste disposal costs could have a very significant effect on the Copper Oxide process; however, the effect becomes significantly lower as the coal is washed.

Probabilistic Results

The effects of uncertainty have a marked influence on capital and annualized costs for the two systems. Figure 8 illustrates how the probabilistic capital cost for three system components (FGD, SCR and copper oxide processes) compares to the deterministic values based on nominal assumptions. For the wet FGD system, the net effect of the assumed uncertainties is a high probability of lower capital costs relative to the deterministic value. These cost reductions are associated principally with the elimination of redundant scrubber trains and the use of larger absorbers. For the SCR system, a less optimistic picture of capital cost emerges. Higher costs are associated principally with concerns over the performance of SCR systems

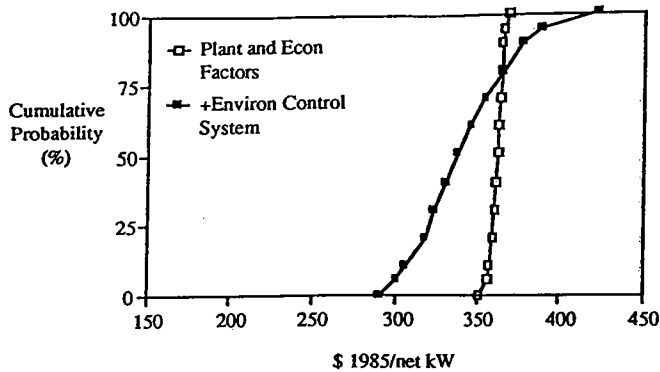


FIG 9. Effect of Different Uncertainties on Total Pollution Control Capital Cost: Wet FGD/SCR Plant

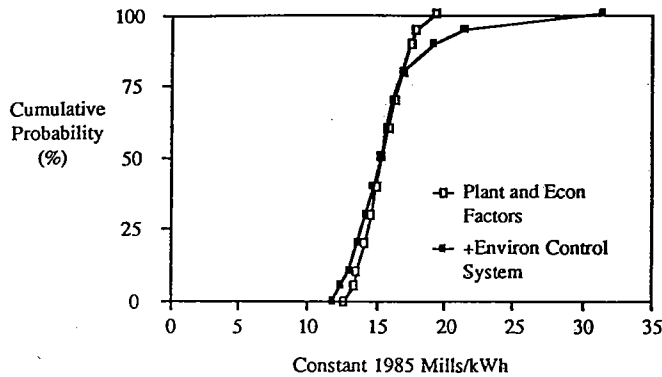


FIG 10. Effect of Different Uncertainties on Total Levelized Pollution Control Cost: Wet FGD/SCR Plant

on high sulfur U.S. coals. For the copper oxide process, the overall probabilistic result suggest a slightly higher potential for lower capital costs relative to the nominal assumptions. The elimination of redundant absorber trains and lower sorbent cost play key roles in achieving these savings.

In Figures 9-12, we show the incremental effects of selected uncertainties on total capital and annualized pollution control costs for the conventional and advanced plant designs. First, the effects of uncertainties only in plant and financial factors (Table I) are displayed with all environmental control system parameters kept at their nominal values. Then, the additional uncertainty due to environmental control system parameters are added to give the overall result for each power plant system. For capital costs, the uncertainty in environmental control system parameters dominates the overall result. Capital costs for the copper oxide plant (Figure 11) vary by approximately minus \$65/kW to plus \$105/kW from the mean value of \$310/kW. For the conventional plant (Figure 9), the capital cost range is narrower, varying from approximately \$50/kW lower to \$85/kW higher than the mean value of \$340/kW.

The results for levelized pollution control costs present a somewhat different picture. Plant and financial factors play a more significant role in the overall uncertainty, especially for the conventional process design (Figure 12). Uncertainty in the annual average capacity factor accounts for a significant portion of this effect. The additional uncertainty in environmental control systems parameters broadens the overall range of levelized cost to nearly factor three; an 80 percent confidence interval ranges from 10.6 to 19.8 mills/kWh, with a mean value of 15.2 mills/kWh. For the conventional plant design (Figure 10), the total levelized cost varies by a factor of 2.6, due primarily to the uncertainty in SCR catalyst life. An 80 percent confidence interval here encompasses annualized cost ranging from 13.0 to 19.1 mills/kWh with an identical mean value of 15.2 mills/kWh.

Figures 13 and 14 next compare the total capital and annualized costs of the conventional and advanced power plant systems, including the integrated system design using coal cleaning in conjunction with the of copper oxide process. Without coal cleaning, there is a good probability of the copper oxide system capital cost being less than the conventional plant, al-

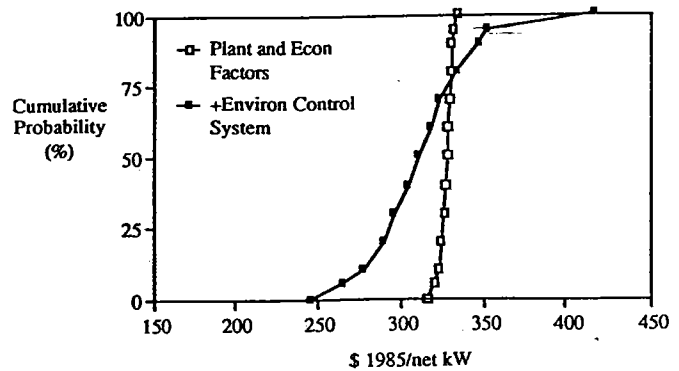


FIG 11. Effect of Different Uncertainties on Total Pollution Control Capital Cost: Copper Oxide Plant

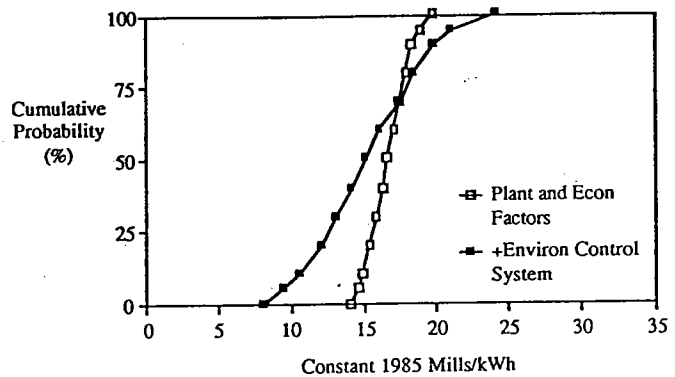


FIG 12. Effect of Different Uncertainties on Total Levelized Pollution Control Cost: Copper Oxide Plant

though on an annualized basis (which is the more appropriate measure for comparison) the copper oxide process stands only a 50 percent chance of being less expensive. The odds of a *significant* cost reduction (e.g., 20 percent or more), however, are very slight.

A much more pronounced advantage for the copper oxide process is seen for the integrated design including coal cleaning. Compared to the convention system, the likelihood of the copper oxide plant with coal cleaning being at least 20 percent lower in capital cost is excellent; the probability of a 20 percent lower annualized cost is also very good, approximately 80 percent. Thus, the combined SO₂/NO_x removal system could indeed have a significant cost advantage over conventional technology in this case if current judgments regarding performance and economic uncertainties are correct.

CONCLUSION

We have attempted to illustrate how a probabilistic analysis can help provide insights regarding the comparative costs of environmental control systems, as well as opportunities for the most successful applications of new processes. The stochastic modeling framework described in this paper allowed the uncertainties in key technical and economic parameters to be quantified, and their implications for overall system design and cost to be analyzed. This capability is especially important for comparing new processes for combined SO₂/NO_x removal to currently commercial technology. Results for the fluidized bed copper oxide process indicated a higher likelihood of significant cost savings in systems using washed (3%S) coal than in systems using higher sulfur run-of-mine coal. The likelihood of future cost reductions in conventional environmental control technology also was seen to be important in evaluating new process concepts.

Probabilistic analysis also can help identify research areas of greatest importance in reducing key uncertainties. In this context, it has direct applications to R&D planning and research management. By making it easy to ask a wide variety of "what if" questions, and to test the implications of alternative views, quantitative analysis can help inform professional judg-

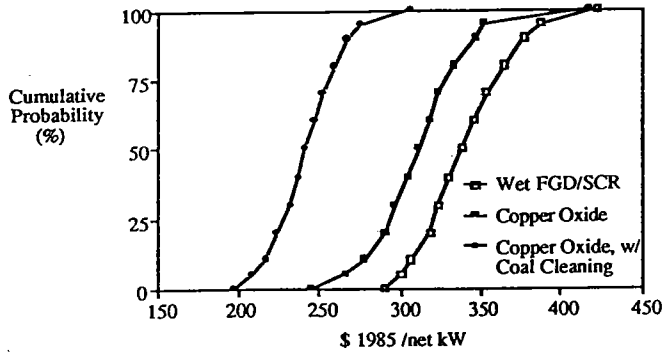


FIG 13. Total Pollution Control Capital Cost

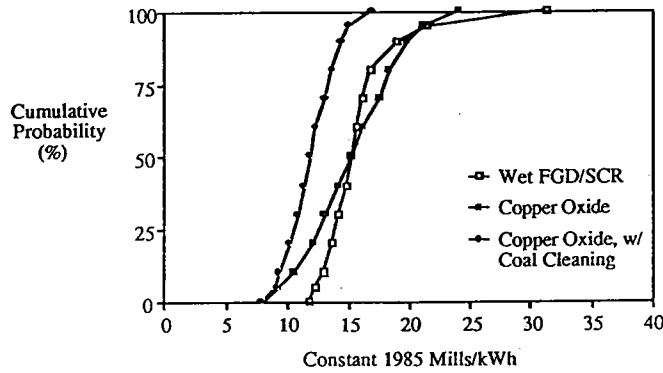


FIG 14. Total Levelized Pollution Control Cost

ments regarding research opportunities and risks, and help identify robust designs for future environmental control systems.

Until recently, the computing power needed to perform the type of probabilistic analysis described here has been available only on mainframe or mini-computers. However, the recent advent of powerful and relatively low cost computer workstations now allows analysis tools such as the IEC model to be conveniently used in much the same way as with smaller personal computers now in widespread use. A Sun 3/50 workstation with a 71 megabyte hard disc is the current configuration employed at Carnegie Mellon. An option using an Apple Macintosh II computer is currently being developed.

Further development of the IEC model is focused principally on the addition of new process options for pre-combustion and post-combustion pollutant removal, and the refinement of existing performance and cost models for current and advanced technologies. Extension of the probabilistic framework also will include new graphics and user interface capabilities to facilitate use of the software by "non-expert" operators. Distribution of the software for use by research sponsors is anticipated in the near future.

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