

Probabilistic Evaluation of Advanced SO₂/NO_x Control Technology

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A new probabilistic modeling environment is described which allows the explicit and quantitative representation of the uncertainties inherent in new environmental control processes for SO₂ and NO_x removal. Stochastic analyses provide additional insights into the uncertainties in process performance and cost not possible with conventional deterministic or sensitivity analysis. Applications of the probabilistic modeling framework are illustrated via an analysis of the performance and cost of the fluidized bed copper oxide process, an advanced technology for the control of SO₂ and NO_x emissions from coal-fired power plants. An engineering model of a conceptual commercial-scale system provides the basis for the analysis. The model also captures interactions between the power plant, the SO₂/NO_x removal process, and other components of the emission control system. Results of the analysis address payoffs from process design improvements; the dependence of system cost on process design conditions and the availability of byproduct markets; and the likelihood that the advanced process will yield cost savings relative to conventional technology. The implications of case study results for research planning and comparisons with alternative systems also are briefly discussed.

For all technologies in an early phase of development there are significant uncertainties in performance and cost estimates for commercial-scale systems. To explicitly characterize such uncertainties, and to evaluate the overall uncertainty in process costs, a probabilistic modeling framework

Implications

Research planning and technology selection decisions for advanced environmental control systems often are hindered by unreliable performance and cost estimates prepared during the early stages of technology development. To gain insight into both the risks and payoffs of a new technology, explicit characterization of process uncertainties is postulated as a key feature of a robust research planning method. The probabilistic modeling method described here allows the effects of uncertainties in multiple performance and cost parameters to be evaluated explicitly and systematically. The information obtained from probabilistic analysis can be used by industrial and governmental decision-makers to make more fully-informed decisions regarding research priorities, investments, and market potential based on explicit characterizations of the technological risks.

has been developed and implemented in a non-procedural interactive modeling environment for performing probabilistic analysis.¹⁻³ The Integrated Environmental Control Model (IECM) includes conventional and advanced technologies for pre-combustion, combustion, and post-combustion environmental controls. Uncertainties in process parameters are characterized using a variety of user-specified probability distribution functions. The use of a probabilistic method allows engineers to make judgments at a disaggregated level about uncertainties in specific process performance and cost parameters. The resulting uncertainties induced in model outputs are then estimated using median Latin hypercube sampling, a variant of Monte Carlo simulation. Details of the modeling system design and software are provided in Reference 1.

The objective of process design typically is to minimize the cost of achieving a given level of performance (e.g., an SO₂ removal efficiency). Thus, process engineering and economic models typically are developed and used to evaluate the effect of controllable design parameters on process performance and revenue requirements. However, these evaluations often ignore the many uncertainties which can affect performance and cost. In contrast, a probabilistic approach yields several important advantages relative to conventional deterministic or sensitivity analysis. For one, probabilistic analysis provides information on the *likelihood* as well as range of possible outcomes for a given design. The effect of many uncertainties interacting simultaneously is quantified, not just the effect of one or two variables with all other parameters held constant (as in sensitivity analysis). As a result, probabilistic process analysis can lead to design decisions and insights different from those obtained from simple deterministic analyses. Stochastic modeling also provides better insights into cost uncertainties than traditional contingency factors used for economic evaluations.

Illustrative Case Study

The fundamental building blocks of the probabilistic modeling system are: (1) engineering (mass and energy balance) process models for each technology of interest; (2) companion economic models for capital cost, operating costs, and annualized cost; and (3) an integrated software design allowing for systematic treatment of key plant parameters and interactions among plant or system components. Such models have been developed for a number of environmental control technologies.¹

Use of the probabilistic modeling framework is illustrated here for the fluidized bed copper oxide process, an advanced technology for controlling SO₂ and NO_x emissions from coal-fired power plants. This process has been

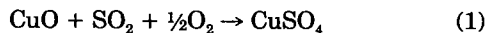
under development at the U.S. Department of Energy's Pittsburgh Energy Technology Center (DOE/PETC) and tested on a small scale. Data from these tests, together with fundamental mass and energy balances, were used to develop a performance model of the process. Studies of projected costs for commercial-scale systems formed the basis for an economic model.

Using the IECM framework, the impact of the copper oxide process on the overall power plant (including downstream flue gas equipment and waste disposal/recovery systems) can be assessed. An integrated design analysis has been used to select optimal values of key process design parameters. The results of the design analysis formed the basis for a set of case studies in which the advanced technology is compared to conventional emission control systems for SO₂ and NO_x removal.

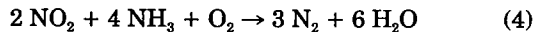
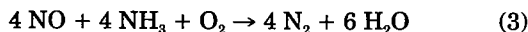
Process Overview

The copper oxide process is designed to achieve 90 percent removal of both SO₂ and NO_x from power plant flue gases. To achieve this performance with conventional (baseline) technology, a wet flue gas desulfurization (FGD) system for SO₂ control and a selective catalytic reduction (SCR) system for flue gas NO_x control would be used. In contrast the copper oxide process combines SO₂ and NO_x removal in a single reactor vessel. The process is regenerative, producing a marketable sulfur or sulfuric acid byproduct in lieu of a solid waste containing spent sorbent. A simple schematic of a power plant with the copper oxide process is shown in Figure 1. A more detailed schematic of the copper oxide process is shown in Figure 2.

In a commercial-scale process, a bed of copper-impregnated sorbent, consisting of small-diameter (e.g., 1/8 inch) alumina spheres, is fluidized by the power plant flue gas. Removal of SO₂ and SO₃ in the flue gas occurs by reaction with copper oxide in the sorbent:



NO_x is removed by reaction with ammonia injected into the flue gas upstream of the absorber. The reaction is catalyzed by copper sulfate and promoted by the mixing within the fluidized bed:⁴



The absorber reactions are exothermic. For a high sulfur coal, the increase in flue gas temperature may be as much as 100°F for 90 percent sulfur removal.⁵ This incremental thermal energy can be recovered in the power plant air preheater, resulting in an energy credit.

The sulfated sorbent is transported from the fluidized bed absorber to a solids heater and then to a regenerator. Regeneration of the sorbent occurs by reaction with methane, converting the copper sulfate and unreacted copper

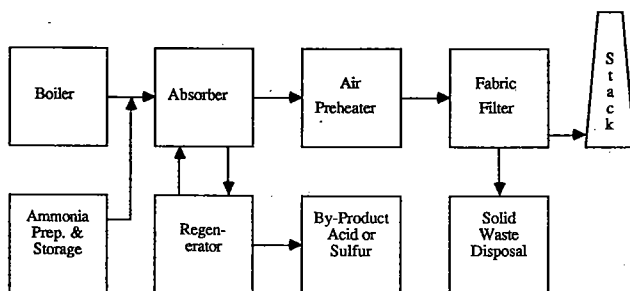


Figure 1. Coal-fired power plant design with a copper oxide emission control system.

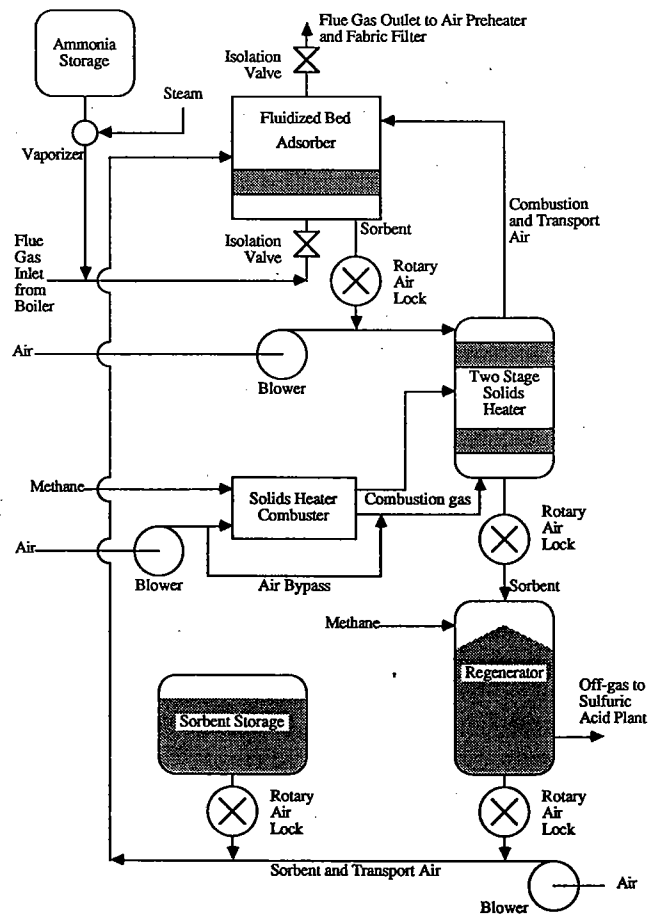
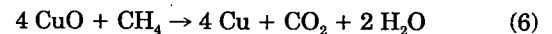
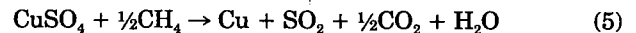


Figure 2. Schematic diagram of the PETC fluidized bed copper oxide process for coal-fired power plant flue gas SO₂ and NO_x removal process.

oxide to elemental copper, and producing an off-gas containing sulfur dioxide:



The off-gas is further processed to recover either sulfuric acid or elemental sulfur. Sulfuric acid is recovered by a sulfuric acid plant containing a three-stage catalytic converter. To recover elemental sulfur, a modified Claus plant may be used instead. A portion of the SO₂ in the off-gas must be converted to H₂S using methane in order for the Claus reaction to occur. The regenerated sorbent is transported back to the absorber. When the sorbent contacts the transport air, an exothermic chemical reaction occurs:



Additional details of process development may be found in References 6 through 10.

Process Performance Model

The copper oxide process performance model includes the fluidized bed absorber, sorbent heater, regenerator, solids transport system, and ammonia injection system. The model also characterizes the performance of an integrated sulfuric acid or sulfur plant, and the power plant air preheater. Material and energy balances are developed for 12 chemical species that are traced throughout the system. These species include components of the flue gas, sorbent, transport air, regenerator off-gas, and a number of other process streams. The mass balances account for the stoichiometry and conversion rate of Reactions 1 through 7. An energy balance for each process area is calculated based on

the mass balance and elemental reference state enthalpy data for each chemical species. Details of the performance model are available elsewhere.⁵

The sorbent flow rate is a key parameter that affects the mass and energy balances, sizing, and cost of most components of the copper oxide process. The total sorbent mass flow rate, including copper oxide, unregenerated copper sulfate, and the alumina substrate, is given by (see nomenclature):

$$m_s = \left(\frac{W_{\text{CuO}}}{X_{\text{Cu}}} \right) [M_{\text{CuO}} + M_{\text{CuSO}_4} (1 + 1.260X_{\text{Cu}})] \quad (8)$$

where

$$M_{\text{CuO}} = \frac{1}{r} (M_{\text{SO}_2} + M_{\text{SO}_3}) \quad (9)$$

and

$$M_{\text{CuSO}_4} = \left(\frac{\eta_s}{\eta_r} \right) (1 - \eta_r) (M_{\text{SO}_2} + M_{\text{SO}_3}) \quad (10)$$

The conversion rates of Reactions 1 through 4 in the fluidized bed absorber are based on the emission control requirements. The available copper-to-sulfur (Cu/S) molar ratio required to achieve a specified SO₂ reduction requirement is estimated based on a first-order sulfation reaction kinetics model developed by PETC.¹¹ This model assumes ideal flow in a plug flow reactor and may be written as:

$$\eta_s = \frac{\exp[B(l-r)] - 1}{\exp[B(l-r)] - r} \quad (11)$$

where

$$B = \frac{kDAGZC_o}{W_{\text{Cu}}V_o}$$

$$r = \frac{M_{\text{SO}_2}}{M_{\text{CuO}}}$$

The PETC model accounts for the molar ratio of inlet sulfur oxides to inlet available copper, r , and the amount of available copper oxide initially resident in the fluidized bed per unit molar gas flow, B . Since incomplete regeneration reduces the available copper relative to fresh sorbent, the PETC model must be modified to explicitly include the effect of regeneration efficiency on the Cu/S ratio requirement. An explicit representation for C_o , the weight ratio of copper oxide to alumina in the substrate, can be given as a function of the regeneration efficiency:

$$C_o = \left(\frac{X_{\text{Cu}}}{R - X_{\text{Cu}}} \right) \left[\frac{1}{1 + \left(\frac{\eta_s}{\eta_r} \right) (1 - \eta_r)r} \right] \quad (12)$$

This expression for C_o is used in Equation 11. For the case study, the SO₂ removal efficiency is a model parameter, and Equation 11, with the modified value of C_o , is used to solve for the required copper-to-sulfur molar ratio. The modified equation is solved numerically.

Figure 3 shows model predictions for the copper-to-sulfur molar ratio based on data reported by Yeh and Drummond.¹¹ The model is a function of eight variables, each of which is subject to measurement error. Thus, scatter in the plotted data is expected. Experimental values of the eight input variables were used as the basis for model predictions, which are compared to the experimentally measured Cu/S ratio. The scatter in the predicted Cu/S ratio can be represented statistically by a standard error, which is used later in an analysis of process uncertainties.

For by-product recovery, the elemental sulfur process is capable of 95 percent sulfur conversion, in contrast to 99.5 percent recovery for sulfuric acid plant. Thus, to achieve an

Nomenclature

- A = Absorber area (m²)
- C_o = Weight ratio of available copper oxide to alumina in the sorbent (kg CuO/kg Al₂O₃)
- D = Fluidized sorbent density (kg Al₂O₃/m³)
- G = Molar volume of flue gas (m³/kgmole)
- H = Fluidized bed height (m)
- k = Sulfation reaction rate constant (1/hr)
- M_i = Molar flow rate into absorber of species i (kgmole/hr)
- r = molar ratio of inlet sulfur in flue gas to available copper in sorbent
- r_{an} = Molar ratio of inlet ammonia to nitrogen oxides in the flue gas
- R = Ratio of molecular weights of Cu and CuO
- X_{Cu} = Weight fraction of copper as copper oxide in sorbent
- V_o = Flue gas volume flow rate (m³/hr)
- W_i = Molecular weight of species i, kg/kgmole
- Z = Fluidized bed height (m)
- η_n = NO_x removal efficiency (fraction)
- η_s = SO₂ removal efficiency (fraction)
- η_r = Regeneration efficiency (fraction)

overall 90 percent SO₂ removal, the copper oxide process must be operated at 90.5 percent removal efficiency with sulfuric acid recovery or 94.7 percent removal efficiency with sulfur recovery. Other possible designs, such as recycling tail gas from the sulfur plant to the power plant flue gas, or sulfur plant tail gas treating, were not considered in this study.

The molar ratio of ammonia-to-nitrogen oxides required to achieve a given level of NO_x removal is estimated using a regression model developed from PETC test data.⁵ The model is sensitive to the fluidized bed height and the required NO_x removal efficiency:

$$r_{an} = \exp\left(\frac{\eta_n - 0.131 H - 0.782}{0.367} \right) \quad (13)$$

The model in Equation 13 does not explicitly account for the catalytic effect of copper sulfate that is believed to promote NO_x removal.⁴ However, the catalytic effect has not been well-characterized in the available literature.

Economic Model

Direct capital costs, indirect capital costs, and fixed plus variable operating costs have been modeled for each compo-

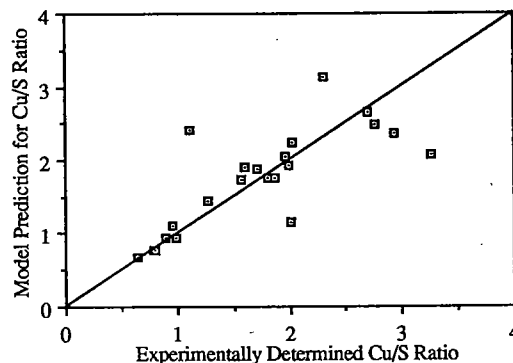


Figure 3. Comparison of experimental and predicted copper-to-sulfur molar ratio. Experimental Cu/S ratio and values of input variables used for model predictions are taken from Reference 11.

ment of the copper oxide system.⁵ The direct capital costs include the absorber, solids heater, regenerator, solids transport, ammonia injection, flue gas handling, incremental air preheater sizing, and by-product recovery plants. These costs are estimated using "capacity-exponent" scaling relationships based on key process parameters.

Indirect capital costs, including engineering, design, supervision, contractor, construction expense, and contingencies, are based on the total direct costs. Other items included in the total capital requirement are interest during construction, royalties, pre-production costs, inventory capital, initial chemicals, and land. Fixed operating costs include operating and maintenance labor, maintenance materials, and administrative labor. Variable operating costs include makeup sorbent, ammonia, methane, electricity, and credits for by-product sales and recovered energy in the air preheater, which reduces coal consumption.

Since the performance and cost of major components of environmental control systems are interrelated, cost comparisons in this paper are based on the total pollution control cost for the power plant. Thus, the total levelized costs presented here include the copper oxide process, a fabric filter particulate collector, solid waste disposal, and any incremental changes to the power plant associated with air preheater modifications and energy credits. For integrated designs employing coal cleaning, the incremental cost of the cleaned coal is also included. All costs of pollution control are expressed as an incremental cost of electricity generation, and constant dollars, which exclude inflation effects, are used throughout the analysis. The capital recovery and variable cost levelization factors are calculated using standard methods described by the Electric Power Research Institute.¹² Economic models for other pollution control systems (used for comparative analyses) are described in Rubin et al.¹

A probabilistic analysis requires input assumptions or data regarding the uncertainties in key process and economic parameters. For this analysis, the selection of parameters for probabilistic representation was based on a review of data, design studies, statistical analysis, and expert judgments by process developers and the authors. Key process parameters were identified by correlating model cost results with process input uncertainties. For the copper oxide process, the factors which contributed most to the uncertainty in total pollution control cost were found to be the sorbent attrition rate, sorbent regeneration efficiency, and copper-to-sulfur molar ratio required to achieve 90 percent SO₂ removal. Uncertainties in the sorbent cost and plant capacity factor also were significant. Scatter plots did not reveal any strong non-linear dependencies.

A summary of key parameter assumptions for the illustrative case studies is presented in Tables I, II, and III. Table III includes the uncertainty distributions for the copper oxide process, fabric filter, and solid waste disposal system. While these distributions serve primarily to illustrate the probabilistic methodology, a few examples can illustrate the basis for characterizing uncertainty.

As shown in Equation 9, the molar flow rate of unreacted copper oxide entering the absorber depends on the available Cu/S molar ratio. An important factor that affects the Cu/S ratio is the regeneration efficiency. Test results for the Cu/S ratio were based on low (e.g., 30 to 50 percent) regeneration efficiencies.⁸ SMC estimated that a properly designed and sized regenerator, coupled with appropriate heating of the sorbent to reaction temperature, can result in regeneration efficiencies of over 99 percent at a 30 minute residence time.¹³ To characterize uncertainty in the regeneration efficiency, a negatively skewed probability

Table I. Selected input parameter assumptions for case studies.

Model parameter	Deterministic (nominal) value	Probability distribution	Values (or σ as % of mean) ^a
<i>Emission constraints</i>			
Nitrogen oxides	90% Reduction		
Sulfur oxides	90% Reduction		
Particulates	0.03 lb/MBtu.		
<i>Power plant parameters</i>			
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%		
Economizer outlet temp	700°F		
Preheater outlet temp	300°F		
<i>Financial parameters</i>			
Inflation rate	0%		
Debt fraction	50%		
Common stock fraction	35%		
Preferred stock fraction	15%		
Real return on debt	4.6%	Normal	(10%)
Real return on com. stock	8.7%	Normal	(10%)
Real return on pref. stock	5.2%	Normal	(10%)
Federal tax rate	36.7%		
State tax rate	2.0%		
Ad valorem rate	2.0%		
Investment tax credit	0%		
Book life	30 years		
Real fuel escalation	0%	1/2 Normal	$\sigma = 0.06\%$

^a σ = standard deviation. Values in parenthesis are standard deviation as a percentage of the nominal value of the distribution. When the nominal value is zero, the standard deviation is expressed on an absolute basis.

Table II. Selected properties of coals used for case studies (as-fired basis).

Coal property	Illinois No. 6 Coal		Pittsburgh Coal	
	Run-of-mine	Washed ^a	Run-of-mine	Washed ^a
Heating value, Btu/lb	10,190	10,330	13,400	12,900
Sulfur, wt%	4.36	3.09	2.15	1.66
Carbon, wt%	57.0	57.7	74.8	72.1
Hydrogen, wt%	3.7	4.0	4.6	4.5
Oxygen, wt%	7.2	8.4	5.3	5.4
Nitrogen, wt%	1.1	1.1	1.4	1.3
Moisture, wt%	12.3	17.5	2.7	7.9
\$/ton (at mine)	26.10	30.68	33.40	34.99
\$/ton (transport)	7.90	7.90	7.90	7.90

^a Model results for a 30% sulfur reduction on a lb/MBtu basis using conventional coal cleaning (Level 3 plant design).

distribution was therefore assumed with a maximum value of 99.2 percent, representative of nominal expectations, with a small probability that the value could go below 50 percent, representative of actual experience to date. The negatively skewed distribution is qualitatively consistent with the notion of performance shortfalls that are characteristic of innovative chemical process plants.¹⁴

In experiments on a life cycle test unit, the sorbent attrition rate (another key parameter) was reduced to 0.13 weight percent of the sorbent circulation rate after modifications were made to the solids transport system.¹⁰ The test results indicated that solids transport was the primary source of sorbent attrition. However, significant improvements in the attrition rate were expected for a commercial

Table III. Nominal parameter values and uncertainties for the advanced environmental control system.

Model parameter	Deterministic (nominal) value	Probability distribution	Value (or σ as % of mean) ^a
<i>Copper oxide process^b</i>			
Fluidized bed height	48 inches		
Sorbent copper loading	7 wt-%		
Regeneration efficiency	99.2%	-1/2 Normal	(20%)
Fluidized sorbent density	400 kg/m ³	Normal	(10%)
Standard error, Cu/S ratio	0	Normal	$\sigma = 0.39$
Sorbent attrition	0.06%	Normal	(41%)
Ammonia stoichiometry	(calc)	Normal	(6.25%)
Regeneration temp	900°F	Normal	(2%)
No. operating trains	4	Chance	10% @ 1; 20% @ 2; 40% @ 3; 30% @ 4
No. spare trains	1	Chance	50% @ 0; 50% @ 1
Sorbent cost	\$5.00/lb	-1/2 Normal	(25%)
Methane cost	\$4.50/mscf	1/2 Normal	(25%)
Ammonia cost	\$150/ton	Uniform	\$150-225/ton
Sulfuric acid cost	\$40/ton	-1/2 Normal	(30%)
Sulfur cost	\$125/ton	-1/2 Normal	(30%)
Absorber direct cap. cost	(calc)	Uniform	1.0x - 1.5x
Solids heater DCC	(calc)	Uniform	1.0x - 1.5x
Regenerator DCC	(calc)	Uniform	1.0x - 1.5x
Solids transport DCC	(calc)	Uniform	1.0x - 2.0x
Sulfur recovery DCC	(calc)	Uniform	1.0x - 1.2x
Total capital cost	(calc)	1/2 Normal	(10%)
<i>Fabric filter</i>			
Air-to-cloth ratio	2.0 acfm/ft ²	-1/2 Normal	(10%)
Bag life	(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%)
<i>Solid waste disposal</i>			
Land cost	\$6,500/acre	Normal	(10%)
Direct cost	(calc)	Normal	(10%)
Operating cost	(calc)	Normal	(10%)

^a σ = standard deviation. Values in parenthesis are standard deviation as a percentage of the nominal value of the distribution. When the nominal value is zero, the standard deviation is expressed on an absolute basis. For uniform distributions actual ranges of values are shown. For chance distributions, the probabilities of obtaining specific values are shown. A multiplier "x" indicates that the range is based on the value calculated by the model.

^b As part of integration of the copper oxide process with the base power plant, the plant air preheater is resized to maintain an exit flue gas temperature of 300°F.

process. The judgment of one process developer, elicited for this study, was that the attrition would nominally be 0.06 percent, but could have a 90 percent chance of being between 0.02 and 0.10 percent. This judgment formed the basis for the distribution in Table III.

On a commercial scale, measures such as equipment additions or redesigns could lead to significantly higher costs. Results from a Rand study regarding cost growth in pioneer process plants indicate that solids handling systems pose the greatest difficulties in process design and operation.¹⁵ In deterministic analyses, contingency factors normally are used to represent process risks. However, in probabilistic analyses, process contingency factors are supplanted by directly specifying uncertainties as probability distributions in model parameters affecting cost. To represent the uncertainty in current estimates of capital cost, the capital costs for each major equipment area were assigned uniform probability distributions, with the current estimates at the low end of the range. The high end of the ranges represented probabilities that the actual capital cost might increase by up to 50 percent for most process areas and up to 100 percent for the solids transport system. These uncertainties were intended to be representative of the costs likely to be found in a commercial system (e.g., based on a fifth-of-a-kind plant).

Applications to Process Design

The value of a probabilistic process model in identifying process design tradeoffs is illustrated for several copper oxide process parameters. While the specific results apply only to this particular technology, the types of insights found apply more generally to other types of environmental control systems.

Absorber Design

The absorber is the principal vessel for SO₂ and NO_x removal, and the height of the fluidized bed is a key design parameter. "Conventional wisdom" among process developers was that increasing the bed height relative to the nominal design value of 36 inches would increase overall process costs since the higher pressure drop across the bed would increase the flue gas fan energy requirements. However, data indicated that increasing the fluidized bed height also increased the available copper in the bed, reducing the required copper-to-sulfur molar ratio (see Equation 11). This, in turn, reduces the required sorbent flow rate in the system. Because much of the process equipment size is based on the sorbent flow rate, a reduction in sorbent flow yields capital and operating cost savings, offsetting the increased energy costs for the absorber.

The integrated process model allowed these design tradeoffs to be quantified. Figure 4 shows the results of both a deterministic and probabilistic simulation of the pollution

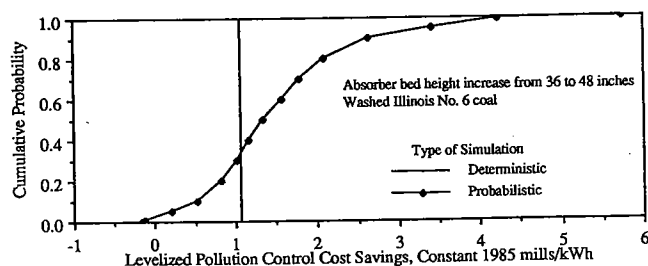


Figure 4. Uncertainty in levelized cost savings due to increasing fluidized bed height. The ordinate shows the overall probability of being at or below the corresponding abscissa value. These results show a 35 percent chance that the cost savings from increased bed height will be less than the deterministic value, and a 65 percent chance that it will be greater.

control cost savings from increasing the absorber bed height from 36 to 48 inches using a washed Illinois No. 6 coal. The deterministic case uses the nominal parameter values in Tables I-III, while the probabilistic case uses distributions. The probability distribution is shown as a cumulative distribution function (cdf). The range of values of the uncertain variable are given on the abscissa, and the corresponding fractile from the probability distribution is shown on the ordinate. The cdf is the integral of the probability density function (pdf). It gives the overall probability of a parameter being at or below a given value. One minus the cumulative probability value gives the probability of exceeding the corresponding parameter value.

The uncertainty in the cost difference when only the bed height is changed was calculated using identical paired samples for the input distributions which take into account the underlying correlation between the two cases. The probabilistic simulation reveals that there is a very small probability (about two percent) that the increase in flue gas fan operating costs could outweigh the cost reductions associated with reduced sorbent circulation rates. On the other hand, there is a 65 percent chance that the cost savings could exceed the deterministic estimate of about 1.1 mill/kWh, with about a 10 percent chance the savings could be over 2.6 mills/kWh. The skewness of the uncertainty distribution in Figure 4 results from assumptions about key uncertain parameters such as the regeneration efficiency. Similar results were obtained for other coals (e.g., run-of-mine Illinois No. 6 and Pittsburgh No. 8) and for other sorbent copper loadings (e.g., 5 and 10 percent).

Sorbent Loading

Increasing the sorbent copper content can reduce the sorbent mass flow. The primary tradeoff is the potential for increased sorbent cost and attrition. An engineering study for DOE, however, reported that copper loadings between 5 and 11 percent have comparable attrition characteristics and similar manufacturing costs.¹⁶ To date, most testing has been with sorbents of five to seven percent copper.^{9,10,17} Figure 5 shows the effect of increasing the sorbent copper loading from 5 to 10 percent for a washed Illinois No. 6 coal. The figure also shows the associated uncertainty in levelized revenue requirement. As the copper content increases, the median and variance of the revenue requirement decrease. There is a significant cost advantage for the seven percent sorbent compared to the five percent case, with a mean savings of 2.3 mills/kWh. Additional savings may be realized by increasing the copper content to 10 percent. These results indicate that additional research on sorbent attrition at the higher copper loadings is merited.

Energy Recovery System

Another process integration issue is the recovery of energy added to the flue gas by the exothermic reactions in

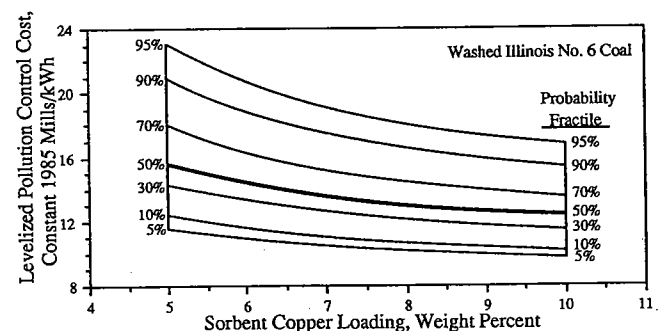


Figure 5. Uncertainty in levelized pollution control cost vs. sorbent copper loading.

the fluidized bed absorber. For the deterministic parameter assumptions, in Table III, the incremental capital cost of the enlarged preheater slightly outweighed (by only 0.01 mills/kWh) the cost savings associated with a reduced fabric filter size and an increased energy credit. However, when the same analysis was performed including uncertainties, the likelihood of a small cost advantage from enlarging the air preheater was found (Figure 6). The difference in results was due to the skewness of many of the distributions assigned to key parameters in the probabilistic model.

Integrated Coal Cleaning

Because many of the costs of the copper oxide process are sensitive to the sorbent flow rate, which in turn is proportional to the coal sulfur content, a reduction in sulfur content through coal cleaning can lower the cost of the process. The integrated environmental control model determines how these savings compare to the increased cost of cleaned coal.

As in the air preheater sizing analysis, deterministic and probabilistic simulations yielded qualitatively different results regarding the net cost savings associated with using a washed Illinois No. 6 coal. As shown in Figure 7, the deterministic analysis indicated an overall cost penalty, whereas results of the probabilistic simulation ranged from a net cost penalty to a 55 percent chance of a cost savings. The cost penalty outcomes stem from the low copper-to-sulfur molar ratios that are achievable with high regeneration efficiencies. In such instances, the process cost savings from lower sorbent circulation rates are too small to offset the higher coal prices associated with coal preparation. The probabilistic analysis, however, reflects the possibility of lower regeneration efficiencies, requiring higher sorbent circulation rates. In these cases, the benefits of a lower sulfur content outweigh the costs of coal cleaning, yielding a net savings.

The degree of sulfur reduction achieved through coal cleaning also affects the cost results. Figure 8 shows the mean cost of each component of the emissions control system associated with various levels of coal preparation. For the example above, a 30 percent sulfur reduction was assumed. Separate analyses for the Pittsburgh No. 8 coal indicated that the cost of coal cleaning was always larger than the incremental savings for the copper oxide process. Similarly, results for the conventional FGD/SCR plant indicated that run-of-mine coals always gave the least cost solution. In the comparisons that follow, therefore, coal cleaning is assumed only for the copper oxide systems with the Illinois No. 6 coal.

Applications to Economic Evaluation

A key measure of the viability of advanced environmental control systems is whether they yield a cost savings compared to currently available technology. For comparative analyses, an integrated emission control system including the copper oxide process is compared to a baseline system

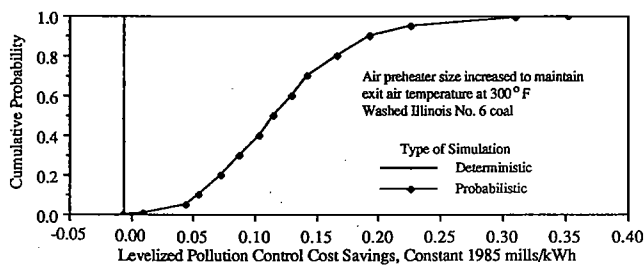


Figure 6. Uncertainty in levelized cost savings due to enlarging the air preheater. Results show a 99 percent probability that the savings will exceed the best guess deterministic value.

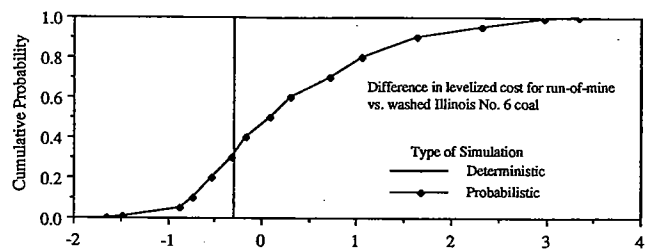


Figure 7. Uncertainty in levelized cost savings due to coal cleaning. Results show a 30 percent chance that the savings will be less than the deterministic value, and a 70 percent chance that it will be greater. Furthermore, there is a 55 percent chance that the cost savings will be positive.

with FGD and SCR. The parameter assumptions and uncertainties for the FGD/SCR system are given in Table IV.

Because many of the input parameter distributions are common to both systems (e.g., financial parameters, base plant characteristics, solid waste disposal, and ammonia cost), there is, in general, a positive correlation between the cost distributions for the two systems. Therefore, as discussed earlier, probability distributions again have been calculated for the cost differences between the copper oxide and FGD/SCR systems using paired, samples of input distributions for each system.

Figure 9 shows the differences in levelized pollution control costs expressed as cumulative distribution functions for four different cases (two coal and two sulfur recovery options). A positive difference indicates that the copper oxide process is less expensive than the FGD/SCR system. This was found to be true for all cases when the median results (i.e., 50 percent probability) are considered. In all cases, the cost savings with copper oxide were higher for the medium sulfur Pittsburgh coal than for the high sulfur Illinois coal.

Figure 9 also shows up to a 30 percent chance that with Illinois No. 6 coal the copper oxide process might be more expensive than the FGD/SCR system. This result stems primarily from the possibility of high operating costs (e.g., for sorbent, etc.). In all cases, however, there is considerable uncertainty in the magnitude of potential cost savings using the advanced technology. For the Illinois No. 6 coal with sulfur recovery, the 90 percent probability range (a common measure of uncertainty defined as the range between the 5th to 95th percentiles) is -5 to 8 mills/kWh. For the Pittsburgh No. 8 coal, the range is 1 to 10 mills/kWh. This indicates that the copper oxide process is likely to be most attractive with medium rather than high sulfur coals. In all cases, there is a small probability that the cost savings could be significantly higher.

Conclusion

Significant uncertainties inevitably surround advanced environmental control technologies in the early stages of

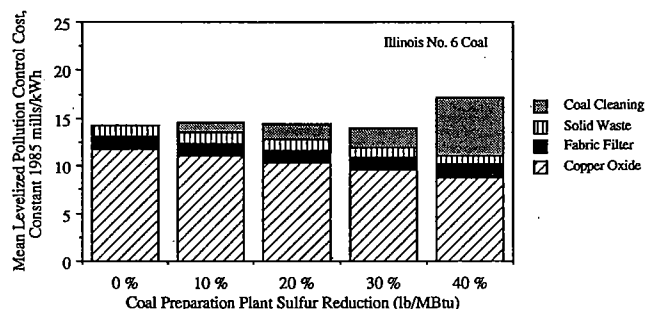


Figure 8. Mean levelized pollution control cost vs. sulfur reduction from coal cleaning. The minimum overall cost occurs with a 30 percent sulfur reduction via coal cleaning.

Table IV. Nominal parameter values and uncertainties for the conventional environmental control system.

Model parameter	Deterministic (nominal) value	Probability distribution	Values (or σ as % of mean) ^a
<i>Wet FGD system</i>			
Molar stoichiometry	(calc)	Normal	(5%)
No. operating trains	4	Chance	10% @ 1; 20% @ 2; 40% @ 3; 30% @ 4
No. spare trains	1	Chance	75% @ 0; 25% @ 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%)
<i>Selective catalytic reduction</i>			
Space velocity	2,850/hr	Normal	(10%)
NH ₃ stoichiometry	(calc)	Normal	(10%)
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	(10%)
<i>Cold-side electrostatic precipitator</i>			
Specific collection area	(calc)	Normal	(5%)
Energy requirement	(calc)	Normal	(10%)
Total capital cost	(calc)	Normal	(10%)
Operating cost	(calc)	Normal	(10%)
<i>Solid waste disposal</i>			
Land cost	\$6,500/acre	Normal	(10%)
Direct cost	(calc)	Normal	(10%)
Operating cost	(calc)	Normal	(10%)

^a σ = standard deviation. Values in parenthesis are standard deviation as a percentage of the nominal value of the distribution. When the nominal value is zero, the standard deviation is expressed on an absolute basis. For uniform distributions, actual ranges of values are shown. For triangular distributions, endpoints and mode are shown. For chance distributions, the probabilities of obtaining specific values are shown. A multiplier "x" indicates that the range is based on the value calculated by the model.

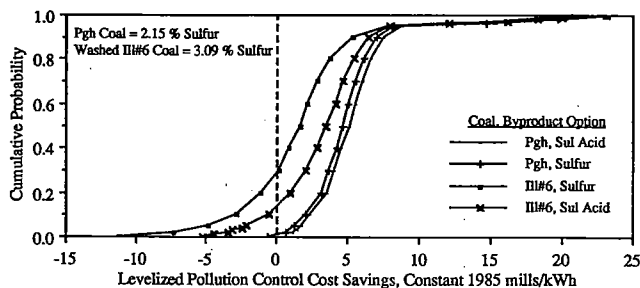


Figure 9. Comparison of levelized pollution control cost savings for copper oxide versus FGD/SCR systems: effect of coal choice and byproduct recovery option. Results show higher probabilities of cost savings for the lower sulfur Pittsburgh coal, and for sulfuric acid rather than elemental sulfur recovery.

development. Thus, engineering performance and cost models developed to evaluate process viability must be capable of adequately analyzing and displaying the consequences of these uncertainties. Toward this end, the probabilistic modeling capability described in this paper allows the effect of uncertainties in multiple performance and cost parameters to be evaluated explicitly. The results give a measure of overall uncertainty in key model outputs, such as cost, and serve to identify the key process variables that contribute most to overall uncertainty.

Case studies for the fluidized bed copper oxide process illustrated potential applications of an integrated environmental control system framework for process design and comparative analyses. Interactions among various components of the environmental control system, which are frequently overlooked in many process studies, were found to significantly influence overall system costs. Probabilistic comparisons between advanced and conventional technologies also provided quantitative assessments of the potential benefits and risks of new technology in various market situations. The potential payoff from process research and

development also may be evaluated using the methods described in this paper.

Of course, as with any other modeling approach, probabilistic methods rely on data and judgments that must be provided by the user. To be sure, different judgments or assumptions can alter the results. But forcing process developers and evaluators to consider uncertainties explicitly (rather than ignore them) in probabilistic engineering models can help improve research planning and management by allowing the implications of alternative judgments to be tested. Indeed, our experience to date suggests that the process of thinking about key parameter uncertainties, as inputs to a model, often is the most valuable component of this approach and fosters improved understanding of the systems being modeled.

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References

1. Rubin, E. S.; Salmento, J. S.; Barrett, J. G.; Bloyd, C. N.; Frey, H. C. "Modeling and Assessment of Advanced Processes for Integrated Environmental Control of Coal-Fired Power Plants," Prepared by the Center for Energy and Environmental Studies, Carnegie Mellon University, for the U.S. Department of Energy, Pittsburgh Energy Technology Center, July 1986.
2. Henrion, M. "The Value of Knowing How Little You Know: The Advantages of a Probabilistic Treatment of Uncertainty in Policy Analysis," Ph.D. Thesis, School of Urban and Public Affairs, Carnegie Mellon University, Pittsburgh, PA, March 1982.
3. Henrion, M.; Wishbow, N. *Demos User's Manual: Version 3*, Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, 1987.
4. Drummond, C. J.; Yeh, J. T.; Joubert, J. I.; Ratafia-Brown, J. A. "The Design of a Dry, Regenerative Fluidized Bed Copper Oxide Process for the Removal of Sulfur Dioxide and Nitrogen Oxides from Coal-Fired Boilers," 78th Annual Meeting of the Air Pollution Control Association, June 16-21, 1985.
5. Frey, H. C. "Performance and Economic Model of the Fluidized Bed Copper Oxide Process," Master's Thesis, Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA, May 1987.
6. Radian Corporation, "The Evaluation and Status of Flue Gas Desulfurization Systems," Prepared for the Electric Power Research Institute, EPRI CS-3322, January 1984.
7. Demski, R. J.; Gasior, S. J.; Bauer, Jr., E. R.; Yeh, J. T.; Strakey, J. P.; Joubert, J. I. "Simultaneous Removal of SO₂ and NO_x From Flue Gas Employing a Fluidized-Bed Copper Oxide Process," 1982 Summer Session of AIChE, August 29 to September 1, 1982.
8. Yeh, J. T.; Demski, R. J.; Strakey, J. P.; Joubert, J. I. "PETC Fluidized-Bed Copper Oxide Process for Combined SO₂/NO_x Removal from Flue Gas," AIChE 1984 Winter National Meeting, Atlanta, March 11-14, 1984.
9. Plantz, A. R.; Drummond, C. J.; Hedges, S. W.; Gromicko, F. N. "Performance of the Fluidized Bed Copper Oxide Process in an Integrated Test Facility," 79th Annual Meeting of the Air Pollution Control Association, Minneapolis, Minnesota 1986.
10. Williamson, R. R.; Morici, J. A.; LaCosse, T. L. "Sorbent Life Cycle Testing, Fluidized Bed Copper Oxide Process," Prepared by UOP, Inc., for the U.S. Department of Energy, Pittsburgh Energy Technology Center, 1987.
11. Yeh, J. T.; Drummond, C. J. "Process Simulation of the Fluidized Bed Copper Oxide Process Sulfation Reaction," AIChE 1986 Spring National Meeting, New Orleans, LA, April 6-10, 1986.
12. EPRI, "TAG(tm)—Technical Assessment Guide, Volume 1: Electricity Supply—1986," EPRI P-4463-SR, Electric Power Research Institute, Inc., December 1986.
13. SMC, "Modeling of the Regenerator Reactor for the Fluidized Bed Copper Oxide Flue Gas Treatment Process," Prepared by Science Management Corporation for the U.S. Department of Energy, Pittsburgh Energy Technology Center, Pittsburgh, PA, May 1984.
14. Merrow, E. W.; Phillips, K. E.; Myers, C. W. "Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants," Prepared by Rand Corporation for U.S. Department of Energy, 1981.
15. Milanese, J. J. "Process Industry Contingency Estimation: A Study of the Ability to Account for Unforeseen Costs," N-2386-PSSP, Rand Corporation, June 1987.
16. SMC, "Technical and Economic Evaluation of Design Optimization Issues Associated With the Fluidized Bed Copper Oxide Flue Gas Treatment Process," Prepared by Science Management Corporation for the U.S. Department of Energy, Pittsburgh Energy Technology Center, Pittsburgh, PA, November 1983.
17. PETC, "Status of the Pittsburgh Technology Center Fluidized-Bed Copper Oxide Process for Flue Gas Treatment: An Interim Report," U.S. Department of Energy, Pittsburgh Energy Technology Center, April 1984.

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