EVALUATION OF THE FLUIDIZED BED COPPER OXIDE PROCESS USING A PROBABILISTIC ENGINEERING MODEL

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ABSTRACT

Performance and economic evaluations of innovative clean coal technologies are typically expressed as deterministic ("best guess") estimates that mask the uncertainties associated with processes at an early stage of development. In this paper applications of a new probabilistic engineering model developed for DOE's Pittsburgh Energy Technology Center (PETC) are described. The example presented analyzes the PETC fluidized bed copper oxide process for simultaneous SO_2 and NO_x reduction from coal-fired power plant flue gas. The copper oxide process is in an early stage of development; however, flowsheets for a commercial scale unit have been developed. The probabilistic modeling capability permits evaluation of the effects of simultaneous variation in uncertain performance and cost parameters for a commercial-scale design. The probabilistic engineering model is applied to: (1) identify the uncertain performance and cost parameters that contribute most to the uncertainty in overall cost; (2) estimate process contingency costs; (3) identify potential cost pay-offs of process improvements; and, (4) compare the advanced process with conventional technology to evaluate potential markets for advanced processes. Results of the analysis indicate specific areas for process design improvements; suggest appropriate contingency factors for the copper oxide process based on probabilistic analysis; and indicate the sensitivity of potential cost savings to design conditions and the availability of byproduct markets.

INTRODUCTION

The purpose of research is to provide and improve information regarding the feasibility, promising applications, optimal designs, uncertainties and risks associated with a new process. The information generated from research can be used by process developers to refine a technology and ultimately by potential process adopters to make a decision about whether, and under what circumstances, to use a new technology. Of concern to a process developer is the prioritization of research needs for a new technology. Which technologies are the most promising for further process development? What conditions favor the selection of the new technology? What specific technical areas require more research? What economic and cost uncertainties affect the economic feasibility of the technology?

This paper presents an evaluation method that can be used to help answer these questions for clean coal technology processes. The salient features of the method include:

- Development of engineering performance and cost models;
- A probabilistic modeling capability to incorporate uncertainties;
- Judgments regarding uncertainties; and
- Exercising of the models to answer these questions:
  - What uncertainties most affect the overall costs?
  - What are the key process design trade-offs?
  - What are the potential pay-offs and risks vis-a-vis conventional technology?

ENVIRONMENTAL REGULATIONS

Current federal new source performance standards (NSPS) applicable to coal-fired power plants require up to 90 percent sulfur dioxide (SO_2) removal, over 99 percent particulate matter (PM) removal, and moderate (about 50 percent) reduction of nitrogen oxides (NO_x) emissions. A conventional emission control system for a new coal-fired power plant typically consists of a wet limestone flue gas desulfurization (FGD) system for SO_2 control, an electrostatic precipitator (ESP) for PM removal, and combustion controls for NO_x reduction. The spent limestone reagent used in the FGD system is disposed of with the power plant solid waste. These systems are all commerically available and well-demonstrated. However, recent commercial experience in Japan and West Germany with selective catalytic reduction (SCR) indicates that 80 to 90 percent NO_x removal may be feasible, although SCR has not yet been applied with U.S. coals (Cichanowicz and Offen, 1987; Damon and Giovanni, 1987).

Alternatives to conventional pulverized coal (PC) combustion, such as integrated coal gasification combined cycle (IGCC) systems, are capable of NO_x emissions below those of PC plants equipped with SCR, as well as high (over 95 percent) levels of SO_2 control (Cool Water, 1986). Furthermore, political concern over acid rain (for which SO_2 and NO_x are precursors) may accelerate the time table for more stringent emission regulations of conventional PC plants. Therefore, there is incentive to develop technology options to reliably achieve stringent emission reductions at minimum cost in a timely fashion.

INTEGRATED ENVIRONMENTAL CONTROL

With the prospect of increasingly stringent emission control has evolved the concept of integrated environmental control. The concept has several dimensions. One is to consider interactions among control methods for air, water, and solid waste emissions control. Another is the integrated use of pre-combustion, combustion, and post-combustion control methods (as distinct from one approach alone). A third dimension is the development of new processes for combined pollutant removal in lieu of separate processes for individual pollutants. Thus, integrated environmental control represents good design practice and provides opportunities to minimize costs for a given set of emission reduction requirements (Carr, 1986).

The DOE Pittsburgh Energy Technology Center (PETC) has conducted research on a number of innovative technologies that combine SO_2 and NO_x removal into a single reactor, and that reduce the solid waste produced by air pollution control systems. One of these technologies, which is used as a case study in this research, is the fluidized bed copper oxide process. Testing of the copper oxide process began at PETC in 1975 and has progressed through several stages in three different test units (Demski *et al*, 1982; Yeh *et al*, 1984; Plantz *et al*, 1986; Williamson *et al*, 1987). Key features of the copper oxide process are that, unlike a wet FGD/SCR system, (1) it combines SO_2 and NO_x removal in a single reactor vessel, and (2) it is regenerative (i.e. the reagent is reused rather than disposed of) and produces a saleable sulfur or sulfuric acid byproduct. The solid waste from a copper oxide system consists only of the fly ash collected in a conventional fabric filter. Conceptual designs of commercial scale copper oxide systems have been developed (e.g., SMC, 1983a). A simple schematic of a power plant with the copper oxide process is shown in Figure 1.

In the copper oxide process, a copper impregnated sorbent, consisting of small diameter aluminum spheres, circulates between a fluidized bed reactor, where SO_2 in the flue gas is removed by reaction with copper oxide in the sorbent, and a regenerator, in which SO_2 is evolved in a reaction of the sulfated sorbent with methane. The SO_2-rich gas from the regenerator is sent to an elemental sulfur or a sulfuric acid plant for byproduct recovery. The regenerated sorbent is returned to the absorber for another cycle. NO_x is removed from the flue gas by reaction with ammonia, which is injected into the flue gas upstream of the absorber. The absorber reactions are exothermic, increasing the temperature of the flue gas. This energy can be recovered in the power plant furnace through additional preheating of the furnace combustion air by the power plant air preheater.

A PROBABILISTIC ENGINEERING MODEL

The copper oxide process is a technology in an early phase of development, for which limited test data and no commercial design or operating experience are available. Uncertainties in system performance at the commercial scale lead to uncertainties in the required size of process equipment and the consumption of materials (e.g., sorbent) and parasitic power. These uncertainties result in uncertainties in capital and operating costs, which are the ultimate measures of interest for comparative analysis. Furthermore, even if process performance were known with certainty, uncertainties regarding the costs of equipment (particularly equipment not previously used in commercial scale service) and reagents remain. To explicitly characterize these uncertainties, and to evaluate the overall uncertainty in process costs, a probabilistic engineering modeling framework has been developed.

Analytic models for a conventional PC power plant, pre-combustion coal cleaning processes, and the components of conventional and advanced post-combustion pollution control systems are available as part of the Integrated Environmental Control Model (IECM), developed under contract to PETC by Rubin et al. (1986). Details of the copper oxide process model, plus models of the power plant air preheater and a sulfuric acid recovery plant, are described elsewhere (Frey, 1987). A number of more recent refinements have been made to the copper oxide process model. These include replacing a regression equation used to estimate the molar ratio of copper in the sorbent to sulfur in the flue gas with a kinetics-based reaction model developed at PETC (Yeh and Drummond, 1986); development of a sulfur recovery plant model based on an engineering study done for PETC (SMC, 1983a); and refinements to some of the input parameters.

The analytic models are based on mass and energy balances for key process equipment. The cost models are based on equipment cost estimates available in the literature, adjusted for plant size using key process stream flow rates and exponential scaling factors. Indirect costs are calculated based on the direct equipment costs. Variable and fixed operating costs are also calculated. The IECM has a capability to report costs in either constant or current dollars. Constant 1985 dollars, which are exclusive of inflation, are used in this analysis.

A unique feature of the IECM is that it is implemented in Demos, a non-procedural interactive modeling environment developed by Henrion (Henrion, 1982; Henrion and Wishbow, 1987) for performing probabilistic analysis. The key uncertainties in process parameters can therefore be characterized using a variety of distribution functions available in Demos. The resulting uncertainty distributions for model outputs are calculated using median Latin hypercube sampling, a variant of Monte Carlo simulation.

SPECIFICATION OF MODEL PARAMETERS AND UNCERTAINTIES

An integrated emission control system consisting of the copper oxide process with integrated coal cleaning, byproduct recovery, and energy recovery via the power plant air preheater, will be compared with a conventional system consisting of wet FGD and SCR. Table 1 summarizes some of the key parameters, including emission constraints, base plant design, and financial parameters, assumed for this analysis. Both deterministic values and probability distributions are indicated in the table. Table 2 summarizes the different coals considered, including both unwashed and cleaned (30 percent sulfur reduction on an energy basis) coals. Table 3 summarizes key input values and distributions for the conventional wet FGD/SCR emission control system, which is taken as a technological baseline in this analysis. The main emphasis of this research is on applying the probabilistic evaluation method to the copper oxide process, assuming the FGD/SCR system as a benchmark. The key inputs and distributions assigned to the copper oxide emission control system are summarized in Table 4. The probabilities assigned to key model inputs reflect judgments on the part of model developers as well as judgments solicited from process developers (Rubin et al., 1986; Frey, 1987; Rubin, Salmento, and Frey, 1988).

IDENTIFICATION OF KEY UNCERTAINTIES

The primary advantage of probabilistic simulation over traditional sensitivity analysis is the simultaneous incorporation of uncertainties in multiple model inputs. The resulting interactions among uncertain variables results in uncertainties in total costs, which are the basis for comparative analysis. The uncertainty in total costs provides information about the technical and economic risk of the technology. Research can provide additional information about uncertain input variables. This may result in changes in parameter values or their uncertainty (such as the standard deviation), and thus affect the overall uncertainty of the technology. This can help focus research on key parameters that reduce the uncertainties that contribute most to the risk of technology failure.

The key parameter uncertainties have been identified by estimating correlations between the primary cost results, such as total revenue requirement or capital cost, and the copper oxide process input uncertainties included in Table 4. Correlations provide a measure of the linear dependence of one distribution on another; however, there are some non-linear relationships in the model, such as between sorbent flow rate and regeneration efficiency. Scatter plots can be used to visually identify non-linear dependencies that may not be well-characterized by correlation coefficients.

The uncertainties which were found to contribute most to the levelized process cost uncertainty included sorbent attrition, regeneration efficiency, and the standard error of the copper-to-sulfur molar ratio, with correlations of 0.55, -0.41, and 0.41, respectively. Scatter plots did not reveal any strong non-linear dependencies. Uncertainties regarding sorbent cost and plant capacity factor were also significant. Uncertainty in sorbent attrition is the largest factor affecting uncertainty in total variable costs, while uncertainty in regeneration and the standard error of the copper-to-sulfur mole ratio significantly affect both capital and operating cost uncertainties. Further research on the copper oxide process should explicitly focus on improving understanding of sorbent attrition, regeneration efficiency, and the variability in the copper-to-sulfur ratio required to achieve a given SO_2 removal efficiency.

ESTIMATING CONTINGENCY COSTS

Nearly all capital cost estimates, whether for a new or existing technology or for a preliminary or detailed cost estimate, include a contingency factor. The contingency is often the single largest expense in the cost estimate, and yet it is also the least documented. A contingency is used to represent additional costs that are expected to occur, but that are not included explicitly in the cost estimate (Milanese, 1987). Contingency factors are typically simple multipliers that are applied to installed equipment costs toward the end of an analysis (e.g., after process area costs have been estimated without regard to their uncertainty). A probabilistic modeling approach supplants the traditional contingency factor approach by incorporating expert knowledge about uncertainties explicitly and at a more disaggregated level (e.g., for specific performance and cost parameters). Furthermore, while simple contingency factors provide no explicit insights into the specific performance or cost parameters that contribute most to the process technical and economic risks, a probabilistic approach permits identification and ranking of the uncertain parameters that contribute most to the overall uncertainty, as discussed above.

The Electric Power Research Institute (EPRI) uses two types of contingency factors: project and process contingency (EPRI, 1986). The "project" contingency is intended to cover the costs of additional equipment or other costs that would result from a more detailed design of a definitive project at a specific site. This implies that as costing proceeds from a preliminary to a detailed final estimate, the project contingency factor should be reduced. In the present analysis, a project contingency of 25 percent is assumed for the copper oxide process, based on an estimate by Science Management Corporation (1983c). The "process" contingency is intended to quantify the additional costs expected due to uncertainty in the technical performance and commercial scale cost of a new technology. This contingency factor is reduced as a technology proceeds from bench scale to full commercial use. Both of the project and process contingency factors are deterministic estimates of additional costs that are expected to occur. However, even in the EPRI Technical Assessment Guide (1986), there is little substantive discussion of how these factors should be derived.

The Rand Corporation conducted a survey of 18 companies in the chemical and petroleum industries to determine the actual methods used to develop contingency factors (Milanese, 1987). The study indicates that contingency factors are often badly under-estimated, which may be leading to bad decisions about certain projects. Rand recommends the greater and more formalized use of experience, the use of a "delphi" technique to get multiple expert inputs, and the inclusion of costs associated with risks and innovation. A probabilistic approach to cost estimating provides a systematic, quantitative method to explicitly incorporate detailed expert judgments about uncertainties. Because the uncertainties contributing to "contingencies" are considered at a disaggregated level, more realistic estimates of performance and cost will generally result.

A deterministic capital cost estimate can include information developed in a probabilistic estimate through appropriate selection of the contingency factor. The contingency factor can be defined as the value that adjusts the deterministic estimate (without contingency) to some specified fractile of the probabilistic estimate. Typically, some "best estimate" value from the probabilistic analysis, such as the mean or the median, would be used. However, if there is significant risk aversion on the part of an investor, who may want to minimize the chance of a cost over-run, then an upper fractile from the probability distribution (e.g., 90th percentile) may be used.

An example of this type of analysis is shown graphically in Figure 2, which shows the results of a probabilistic analysis of the capital cost of the copper oxide process. The mean value of the distribution is found to be $111 million, which is slightly above the median value (50 percent probability) due to the skewness assumed for some of the input parameter probability distributions. For a completely deterministic case using nominal values with no contingencies the cost is found to be $74 million. Thus, the mean value of the probabilistic analysis corresponds to a deterministic overall contingency factor of 80 percent or a 55 percent process contingency, assuming a 25 percent project contingency, as illustrated in Figure 3. The probability of an overrun at this contingency factor is seen to be 45 percent.

The contingency factor estimated in this fashion is significantly higher than the 55 percent value (30 percent process contingency, 25 percent project contingency) assumed in previous analyses (SMC, 1983c). Contributing factors to the difference are the uncertainties assigned to the regeneration efficiency and the capital costs for each major process section, which are skewed. The difference is not surprising, since the previous contingency was based on a rule-of-thumb, rather than a detailed probabilistic risk assessment. The fact that the original estimate seems to be low is also supported by the results of the Rand study, which indicates that contingency factors are generally grossly under-estimated, especially early in process development.

DESIGN TRADE-OFFS AND MARKET NICHES

Analyses regarding trade-offs and potential emission control technology market niches must consider performance and cost interactions between the control technology and the balance of the power plant system, in addition to interactions within the technology itself. Key process trade-offs are identified using probabilistic estimates of the mean costs associated with various design decisions. Comparative analysis of the copper oxide process and an FGD/SCR system are used to identify potential market niches for the new technology.

Design Trade-Offs

A number of controllable design parameters are evaluated to determine their effect on process performance and cost. These design parameters include the fluidized bed height, air preheater size, weight percent of copper in the sorbent, sulfur recovery option, and coal characteristics (including coal cleaning).

The value of the copper oxide process model in identifying process trade-offs is best illustrated by comparing a common assumption with modeling results for different fluidized bed heights. The common assumption is that increasing the fluidized bed height, which reduces the required sorbent flow rate and increases the pressure drop in the bed (increasing the flue gas fan operating costs), results in a net process cost increase. However, the model results indicate otherwise. Because much of the equipment in the copper oxide process, including the sorbent transport system, the solids heater, and the regenerator, are sized based on the sorbent flow rate, a reduction in sorbent flow rate can yield significant capital cost savings. Furthermore, operating costs are reduced, due primarily to lower sorbent replacement costs and lower methane requirements to heat and regenerate the sorbent. Model results indicate a net levelized cost savings as the fluidized bed depth is increased.[1] For example, the mean levelized savings for an increase in bed height from 36 to 48 inches is 1.1 mills/kWh with a washed Illinois No. 6 coal. Therefore, an integrated process model of a technology in the research phase can yield important insights into performance and cost trade-offs.

Optimization of the sorbent copper content is an important area for further research. The primary trade-off is between reducing the sorbent mass flow rate and sorbent attrition. PETC tests have indicated that at a very high sorbent copper loading of 18 percent, the sorbent essentially disintegrates (Yeh and Drummond, 1986). An engineering study for PETC reports that copper loadings from 5 to 11 percent may have comparable attrition characteristics (SMC, 1983b). However, most testing has been with sorbents containing between 5 and 7 percent copper (e.g., Yeh *et al.*, 1984; Plantz *et al.*, 1986; Williamson *et al.*, 1987) Figure 4 shows the effect of increasing the sorbent copper loading from 5 to 10 percent for three coals.[2] The results indicate a significant advantage for the 7 percent copper sorbent compared to the 5 percent copper sorbent. The 7 percent copper sorbent is used as the basis for later case studies. Additional savings may be realized by a further increase to 10 percent weight copper. These results indicate that additional research on sorbent attrition at the higher copper loadings is merited.

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[1] Although the model does not account for additional structural support costs required for the absorber to handle the increased sorbent weight and pressure drop, it is expected that an incremental increase in bed height from the commonly assumed 36 inch bed depth to a 48 inch bed depth can still yield a significant cost savings.

[2] The cost of sorbent is assumed not to vary for moderate increases in sorbent loading. Impregnation of the alumina pellets with copper is a relatively small cost of sorbent production compared to manufacturing the alumina spheres. Sorbent attrition is also assumed not to vary significantly for sorbent copper loadings in the 5 to 10 percent range.

One process integration issue is the recovery of energy added to the flue gas by the exothermic reactions in the fluidized bed absorber. The sizing of the power plant air preheater, which heats the inlet air to the plant furnace, affects the magnitude of the additional energy that can be recovered in the furnace, thereby displacing some coal consumption and resulting in an energy credit. A deterministic "best guess" analysis indicates that there is an overall cost penalty to enlarging the air preheater. However, a probabilistic analysis indicates that an enlarged air preheater does provide an overall cost savings. The difference in results is due to the skewness of many of the distributions assigned to key parameters in the probabilistic model, indicating that there is a value of including the additional information about uncertainty in the analysis. Furthermore, the model accounts for downstream effects, such as the size of the fabric filter particulate collector, which are often neglected by process developers. The cost of the fabric filter is reduced by the larger air preheater, because the fabric filter inlet flue gas temperature, and the corresponding volumetric flue gas flow rate, are reduced. The mean value of the total levelized pollution control system cost saving is 0.32 mills/kWh with a cleaned Illinois No. 6 coal. These potential cost savings, which are revealed by probabilistic modeling and an integrated consideration of downstream effects, are measures of both the value of including uncertainty in the model and the value of an integrated model that accounts for downstream effects.

Another process integration issue is the sulfur byproduct recovery option, which has a significant effect on process costs. Elemental sulfur recovery is more expensive than sulfuric acid recovery, adding to the levelized pollution control costs a mean value of 2 mills/kWh for the cleaned Illinois #6 coal and 0.44 mills/kWh for the unwashed Pittsburgh coal. The sulfur plant consumes a significant amount of methane as a reducing reagent, which is the primary contributor to increasing the system operating costs. Partly because the removal efficiency of the copper oxide process must be increased to compensate for the lower recovery efficiency of the sulfur plant,[3] and partly because the capital cost of an integrated sulfur plant is somewhat higher than a sulfuric acid plant for the cases considered, the total capital cost of a copper oxide system with sulfur recovery is higher than with sulfuric acid recovery. However, market conditions are generally expected to favor the sale of sulfur over sulfuric acid as a byproduct (Burns and Roe Services Corp., 1987). Therefore, even though the system costs are higher, the potentially larger market penetration of elemental sulfur may lead to a larger overall pay-off from R&D.

Identification of Potential Market Niches

The ultimate pay-off from R&D on the copper oxide process is significantly influenced by expected cost savings compared to conventional systems. Key factors which influence the cost savings include the sulfur recovery option and byproduct market, plant size, capacity factor, and coal characteristics. To determine potential market niches, comparisons between copper oxide and conventional FGD/SCR systems are made on the basis of total pollution control system costs, which are exclusive of the base plant and include SO_2, NO_x, and PM removal, solid waste handling, and coal cleaning. Any emission control system-related changes to the base plant are charged to the pollution control system. As a result, interactions among components of the pollution control system and between the pollution control system and the base plant are integrated into the analysis.

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[3] Two other approaches to compensate for the comparatively low sulfur recovery efficiency of the elemental sulfur plant (only 95 percent compared to 99.5 percent for a sulfuric acid plant) are treatment of the tail gas leaving the sulfur plant, which is a common feature of integrated gasification combined cycle (IGCC) designs (e.g., Fluor, 1984) or recycle of the sulfur plant tail gas to the power plant flue gas (SMC, 1983a). These options may yield significant cost savings.

Although the elemental sulfur recovery option is shown to be more expensive than the sulfuric acid option, both systems enjoy levelized cost savings over conventional FGD/SCR systems for a wide range of capacity factors (0.50 to 0.80) and plant sizes (300 MW to 700 MW). For the base case 500 MW plant with a 65 percent capacity factor, the cost savings are 8 percent and 20 percent for the elemental sulfur and sulfuric acid recovery options, respectively, compared to the FGD/SCR system.

The effect of coal cleaning on process costs is an important consideration in comparative analysis. Because many of the costs of the copper oxide process are sensitive to sorbent flow rate, which in turn is proportional to the coal sulfur content, a reduction in the coal sulfur content through coal cleaning can reduce the overall cost of the process in some cases. In contrast, the FGD/SCR system is comprised of separate reactor vessels for SO_2 and NO_x control, both of which are proportional in cost primarily to the flue gas flow rate and not significantly influenced by coal cleaning. Although coal cleaning results in higher coal costs, for the copper oxide process with high sulfur coal this is more than offset by decreased process costs. For medium and low sulfur coals, however, the increased costs of coal cleaning are larger than the reduction in process costs.

As an example, results for the Illinois No. 6 coal are shown in Figure 5 for the copper oxide process with sulfuric acid recovery. The contribution of each emission control process to the total costs is shown in the figure. Integration of 30 percent coal sulfur reduction through coal cleaning with the copper oxide process is shown to reduce levelized costs by approximately one mill/kWh; the cost saving is similar for the sulfur recovery option. For the lower sulfur Pittsburgh coal, coal cleaning increases costs for all the pollution control systems. However, the cost advantage of the copper oxide process is increased for the lower sulfur coal, primarily due to a reduction in sorbent handling requirements. In the remaining comparisons of FGD/SCR and copper oxide systems, optimal levels of coal cleaning are used; i.e., no coal cleaning for the FGD/SCR systems or for the copper oxide systems with the Pittsburgh coal, and 30 percent sulfur reduction through washing for copper oxide systems with Illinois No. 6 coal.

PROBABILISTIC COMPARATIVE ANALYSIS: FOUR CASE STUDIES

Based on the identification of copper oxide process design issues, four case studies involving probabilistic comparisons of copper oxide and conventional environmental control systems were made. These comparisons were made for optimal levels of coal cleaning and for both sulfuric acid and sulfur recovery options. All of these comparisons are based on a 48 inch bed height and 7 percent copper sorbent. Probabilistic comparison of the pollution control systems provides information about the likely cost savings that can be achieved by the new process, as well as the risks that the new technology may be more expensive than existing technology.

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.[4] Therefore, the distributions have been determined for the cost *differences* between the copper oxide and FGD/SCR systems in which samples for the distributions of costs of each system were paired.

Figure 6 shows differences in levelized pollution control costs between FGD/SCR and copper oxide systems for two coals and the two sulfur recovery options. In all cases, the copper oxide process is most likely to be less expensive than the FGD/SCR system; however, for the higher

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[4] In this example, the correlation between the uncertainty distributions of levelized pollution control costs for conventional FGD and advanced copper oxide/sulfuric acid systems is estimated to be 11 percent for optimal levels of coal cleaning with the Illinois No. 6 coal.

sulfur coal there is a substantial risk that the copper oxide process will be more expensive. Taking the case with sulfur recovery and the Illinois No. 6 washed coal as an example, there is nearly a 30 percent probability that the new process will be more expensive than conventional technology, based on the levelized costs. For the medium sulfur Pittsburgh coal, the probability of the new technology being more expensive than the conventional system is negligible. Furthermore, the magnitude of cost savings is likely to be larger for the Pittsburgh coal than for the higher sulfur Illinois No. 6 coal. In all cases, there is considerable uncertainty in the amount of the cost savings. The 90 percent probability range for the Illinois No. 6 coal with sulfur recovery is -5 mills/kWh to 8 mills/kWh. There is a small probability that the cost savings could be significantly higher.

CONCLUSIONS

The foregoing analyses have demonstrated several points about research-phase modeling of a new technology. A probabilistic capability has permitted an evaluation of the effect of simultaneous uncertainties in multiple performance and cost parameters and the identification of key uncertainties contributing most to the uncertainty in process cost. An integrated model of the copper oxide process has permitted the evaluation of interactions involving components of the copper oxide process, the pollution control system, and the power plant. These interactions, which can be overlooked if not included in a systematic modeling framework, significantly influence process costs. Identification of important interactions provides the basis for determining research priorities, such as evaluating the effects of increased bed height on sorbent circulation rate. The explicit characterization of uncertainty in the model provides additional insights that may be overlooked in deterministic analysis, as demonstrated with the air preheater sizing analysis. Integration of pre- and post-combustion pollution control measures can lead to significant cost savings with high sulfur coals, although results indicate that the copper oxide process has an increased comparative advantage over FGD/SCR systems on medium sulfur coals.

While the magnitude of cost savings may be greatest on medium sulfur coals, the copper oxide system appears to dominate FGD/SCR systems for all cases considered. Cost savings appear to be larger for sulfuric acid byproduct recovery systems, although the available markets may be more limited than for elemental sulfur. The availability of byproduct markets will be significant in determining the extent of process application and the pay-off from R&D. Probabilistic comparisons of innovative and conventional technologies provides quantitative information about the risk that a new technology may be more expensive, and the potential pay-off of process research. By explicitly considering uncertainties and key process interactions, the probabilistic engineering models can be used to improve research planning and ultimately to assist potential process adopters in decision making.

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Table 1: Selected Input Parameter Assumptions for Case Studies

Model Parameter	Nominal Value	Probability Distribution	Values (or σ as % of mean)
<u>Emission Constraints</u>			
Nitrogen Oxides	90% Reduction		
Sulfur Oxides	90% Reduction		
Particulates	0.03 lb/MBtu		
<u>Power Plant Parameters</u>			
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		
<u>Financial Parameters</u>			
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	σ = 0.06 %

Table 2. Selected Properties of Coals Used for Case Studies (As-Fired Basis)

	Illinois No. 6 Coal		Pittsburgh Coal	
Coal Property	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)

Table 3. Nominal Parameter Values and Uncertainties for the Conventional Environmental Control System

Model Parameter	Nominal Value	Probability Distribution	Values (or σ as % of mean)[a]
Wet FGD System			
Molar Stoichiometery	(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 %)
Selective Catalytic Reduction			
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 %)
Cold-Side Electrostatic Precipitator			
Specific Collection Area	(calc)	Normal	(5 %)
Energy Requirement	(calc)	Normal	(10 %)
Total Capital Cost	(calc)	Normal	(10 %)
Operating Cost	(calc)	Normal	(10 %)
Solid Waste Disposal			
Land Cost	$6,500/acre	Normal	(10 %)
Direct Cost	(calc)	Normal	(10 %)
Operating Cost	(calc)	Normal	(10 %)

[a] For uniform distributions actual values are shown. For triangular distributions, endpoints and median are shown. For chance distributions, the probabilities of obtaining specific values are shown.

Table 4. Nominal Parameter Values and Uncertainties for the Advanced Environmental Control System

Model Parameter	Nominal Value	Probability Distribution	Values (or σ as % of mean)[a]
Copper Oxide Process[b]			
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	σ = 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 %)
Fabric Filter			
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 %)
Solid Waste Disposal			
Land Cost	$6,500/acre	Normal	(10 %)
Direct Cost	(calc)	Normal	(10 %)
Operating Cost	(calc)	Normal	(10 %)

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[a] For uniform distributions actual values are shown. For triangular distributions, endpoints and median are shown. For chance distributions, the probabilities of obtaining specific values are shown.

[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.

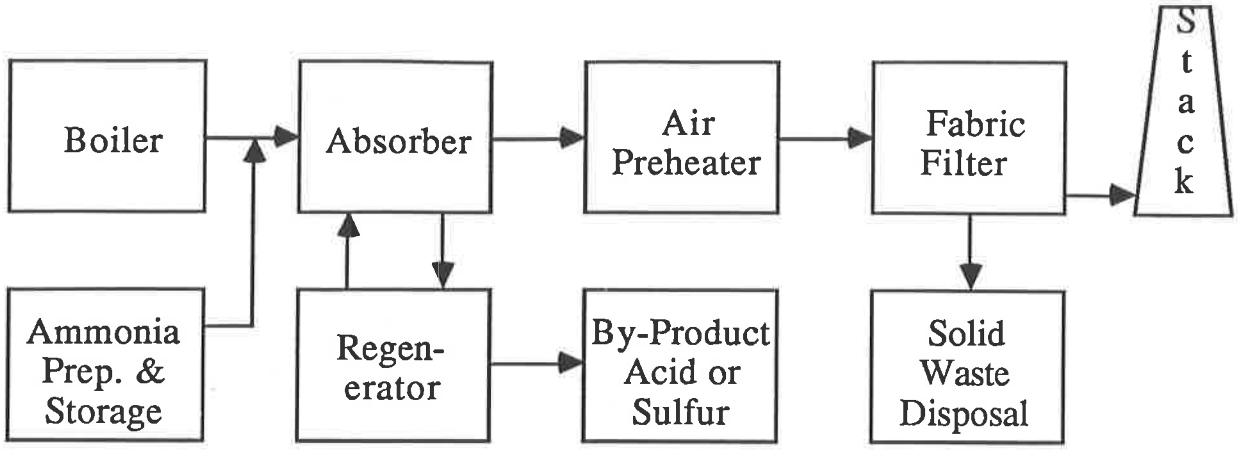

Figure 1. Power Plant Design with a Copper Oxide Emission Control System

Figure 2. Uncertainty in Total Capital Cost for the Copper Oxide Process

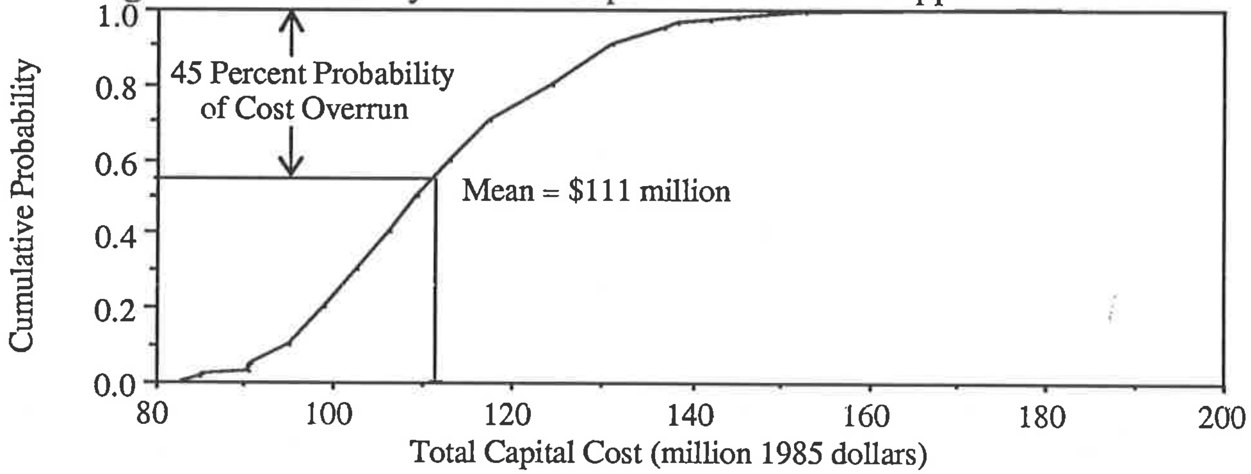

Figure 3. Overall Contingency Factor and Total Capital Cost: Deterministic Analysis of the Copper Oxide Process

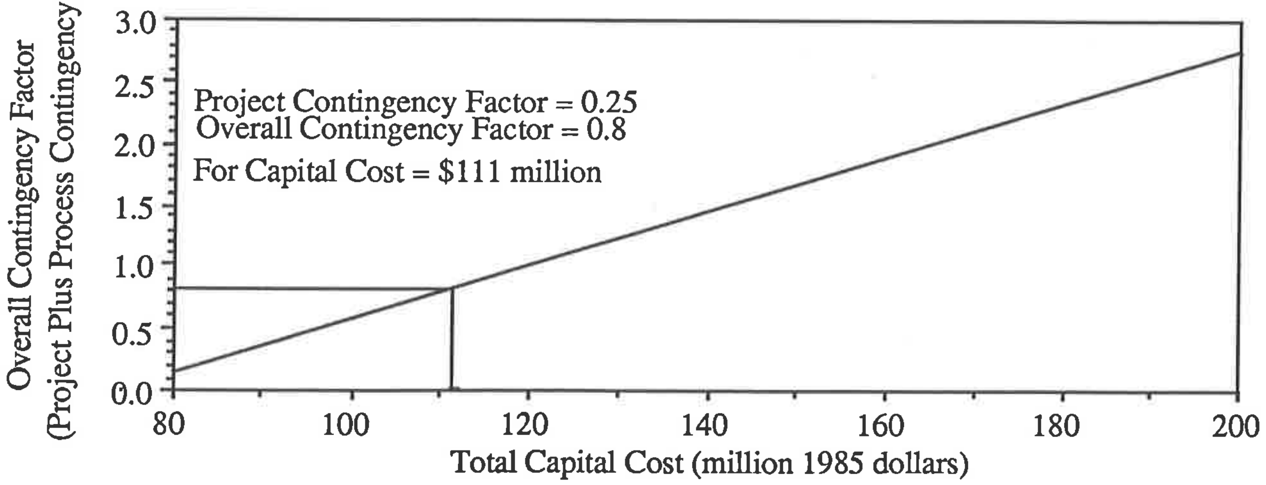

Figure 4. Mean Levelized Pollution Control Costs for Copper Oxide System with Acid Recovery: Effect of Sorbent and Coal Characteristics

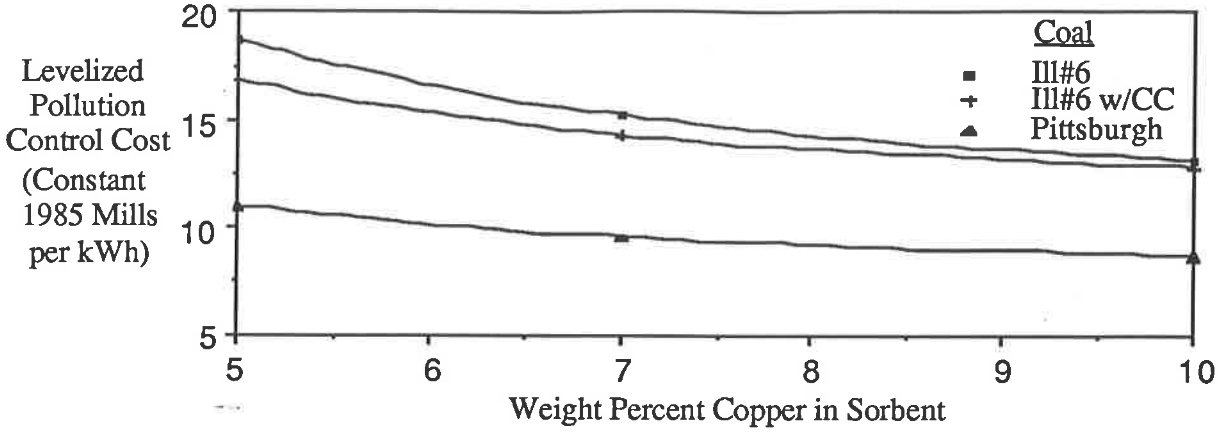

Figure 5. Mean Levelized Pollution Control Cost versus Sulfur Reduction from Coal Cleaning: Copper Oxide/Sulfuric Acid Plant with Illinois #6 Coal

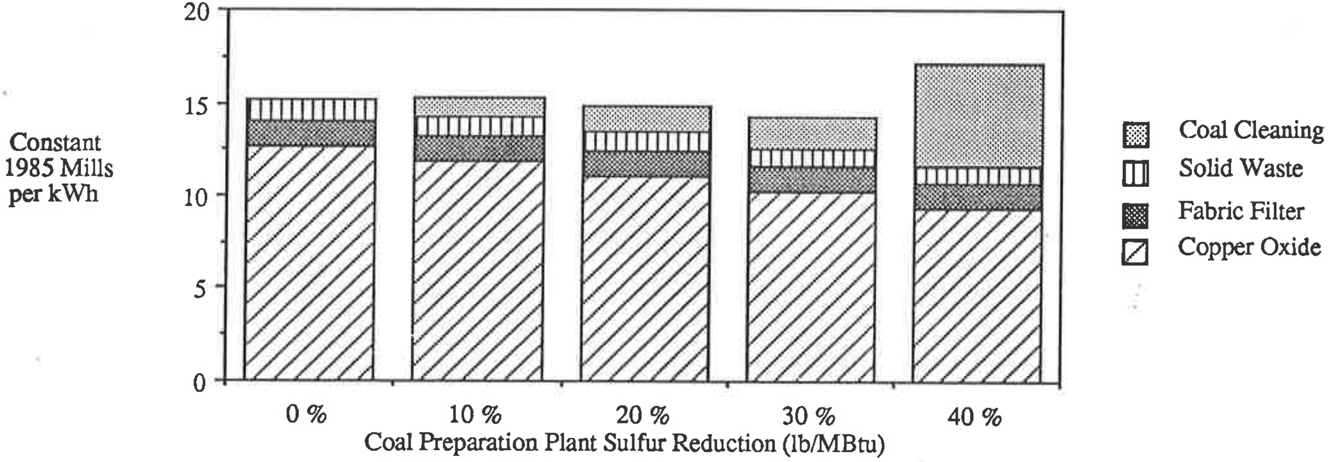

Figure 6. Comparison of Levelized Pollution Control Cost Savings for Copper Oxide vs. FGD/SCR Systems: Effect of Coal Cleaning and Byproduct Recovery Option