DEVELOPMENT AND APPLICATION OF THE INTEGRATED ENVIRONMENTAL CONTROL MODEL

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INTRODUCTION

Over the past two decades, environmental regulations have transformed the design of new coal-fired power plants. Requirements for the control of air pollutants, water pollutants and solid wastes have added considerably to plant complexity, while spurring the development of new, more innovative technology for the removal of pollutants before, during and after combustion. The availability of a larger number of options for meeting emission reduction requirements also has increased the need for systematic methods of evaluating and comparing process alternatives. In particular, there is now an increased need to assess the cost and performance of alternative power plant designs involving both conventional and advanced technologies.

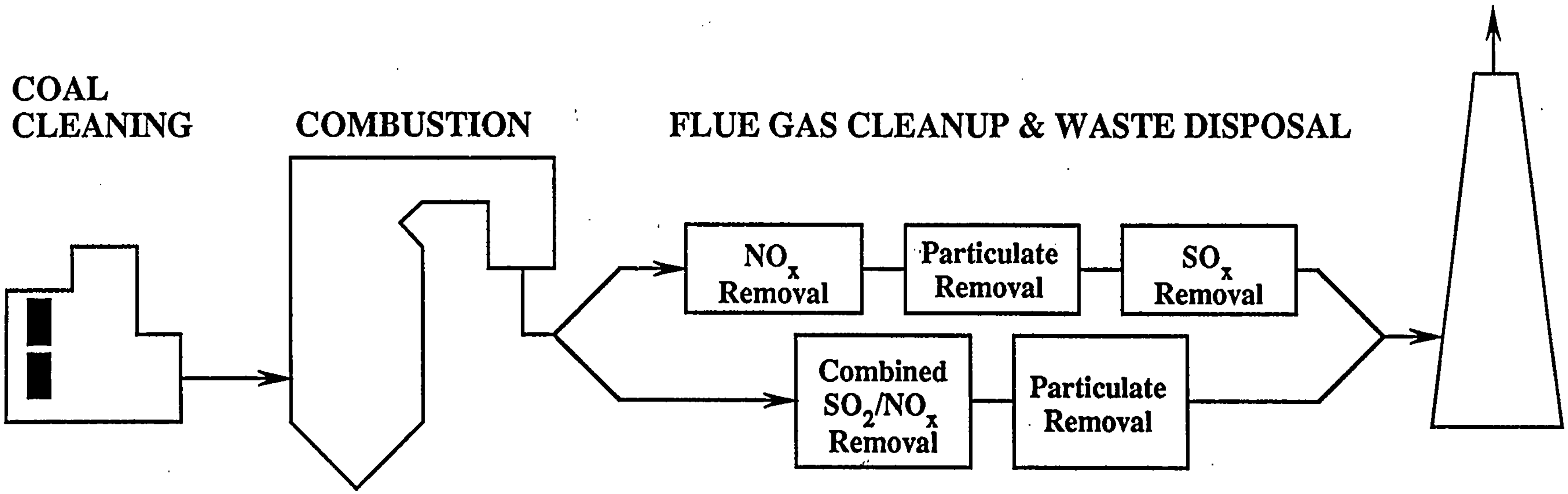
This paper describes an analytical model developed for the U.S. Department of Energy's Pittsburgh Energy Technology Center (DOE/PETC) under Contract No. DE-AC22-87PC79864. The model quantifies the performance and cost of power plant designs that involve user-specified combinations of pre-combustion, combustion, and post-combustion methods of environmental control. A unique feature of the Integrated Environmental Control Model (IECM) is the ability to characterize uncertainty in probabilistic terms, in contrast to conventional deterministic analysis. This capability offers special advantages in comparing advanced technologies at an early stage of development with conventional systems where uncertainties are smaller. This paper reviews the current status of model development and presents an illustrative example of its use. Plans for further model development also are summarized.

MODEL OVERVIEW

The concept of integrated environmental control includes several dimensions. One is the consideration of interactions among control methods used 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 of integration involves 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.

Figure 1 shows the technologies currently included in the Integrated Environmental Control Model (IECM). These include a number of commercially available methods of pollution control, as well as several advanced technologies of interest to DOE/PETC. For each of the technologies listed in Figure 1, a process performance model has been developed to account for mass and energy flows associated with that process. Coupled to each engineering performance model, an economic model also has been developed to estimate the capital cost, annual operating cost and total levelized cost of each technology. Details of these performance and cost models have been reported elsewhere (1, 2).

Figure 1. Integrated Environmental Control Model Technologies



CONVENTIONAL PROCESSES

Plant Designs • Level 2 • Level 3 • Level 4 • Froth Flotation	• Tangential, Wall, Cyclone Firing • Boiler Efficiency • Low No_x Burners	• Selective Catalytic Reduction • Electrostatic Precipitator • Fabric Filter	• Limestone Fgd • Spray Dryer • Ponding • Landfill

ADVANCED PROCESSES

• Coal-pyrite Flotation • Magnetic Separation • Selective Agglomeration • Heavy Liquid Cyclones	• Sorbent Injection	• Copper Oxide • NOXSO Process • Electron Beam	• Sulfuric Acid Recovery • Sulfur Recovery

Running the IECM involves three principal steps. The first is to configure a power plant for analysis. Here, the user specifies the set of pre-combustion, combustion, and post-combustion technologies of interest, along with associated waste disposal method. Next, the user specifies the values of model parameters related to control technology design, power plant characteristics, fuel specifications, and environmental regulatory constraints. Economic and financial parameters also are specified at this stage. Overall, the IECM contains several hundred input parameters covering all technologies in the model. For a typical analysis, on the order of 50 parameters must be specified. Default values for most parameters are incorporated to assist the user. Once all input parameters are set, the model is executed and the desired output results are specified. Several standard reports are incorporated for economic analysis, though the user may easily call for any performance or economic output parameter of interest.

The model currently runs on a Macintosh II computer, but may also be used on a Sun (or equivalent) computer workstation running the Unix operating system. As discussed later, a particular advantage of the Macintosh system is its capability to support a user-friendly graphical interface to facilitate model use.

REPRESENTING UNCERTAINTIES

As noted earlier, a unique feature of the IECM is its ability to characterize input parameters and output results probabilistically, in contrast to conventional deterministic (point estimate) form. This method of analysis offers a number of important advantages over the traditional approach of examining uncertainties via sensitivity analysis. Probabilistic analysis allows the interactive effects of variations in many different parameters to be considered simultaneously, in contrast to sensitivity analysis where only one or two parameters at a time are varied, with all others held constant. In addition, probabilistic analysis provides insight as to the likelihood of certain outcomes, or the probability that one result may be more significant than another. This type of information is generally of greater use than bounding or "worst case" analyses obtained from sensitivity studies.

The ability to perform probabilistic analysis comes from the use of a new software system which uses a non-procedural modeling environment designed to facilitate model building and probabilistic analysis (3). In addition to a number of standard distributions (e.g., normal, lognormal, uniform, chance), the IECM can accommodate any arbitrarily specified distribution for input parameters. Given a specified set of input uncertainties, the resulting uncertainties induced in model outputs are calculated using median Latin Hypercube sampling, and efficient variant of Monte Carlo simulation. Results typically are displayed in the form of a cumulative probability distribution showing the likelihood of reaching or exceeding various levels of a particular parameter of interest (e.g., cost). Examples of model results have been presented previously (1, 4).

MODEL APPLICATIONS

The IECM is intended to support a variety of applications related to technology assessment, process design, and research management. Examples of questions that can be addressed with the IECM include the following:

- What uncertainties most affect the overall costs of a particular technology?
- What are the key design trade-offs for a particular process ?
- What are the potential payoffs and risks of advance processes vis-a-vis conventional technology?

- Which technologies appear most promising for further process development?
- What conditions or markets favor the selection of one system design (or technology) over another?
- How can technical and/or economic uncertainties most effectively be reduced through further research and development?

To address questions like this, a number of case studies have been undertaken using the IECM. As an illustrative example, we show here the case of a new coal-fired power plant employing the fluidized bed copper oxide process for simultaneous SO_2 and NO_x removal. An integrated system design was assumed in which conventional coal cleaning was used along with power plant controls to evaluate the least cost option. Two options for by-product recovery (sulfur and sulfuric acid) also were evaluated. Finally, the analysis was conducted for two different coals (Pittsburgh No. 8 and Illinois No. 6) to examine the effects of differences in coal quality and cost.

Tables 1, 2 and 3 show some of the input parameters and associated uncertainties assumed for this example. For the copper oxide process alone, previous studies using the IECM identified a number of key design trade-offs affecting overall process economics and potential markets for this technology (5). Use of the engineering process model allowed the values of several key design parameters to be specified so as to minimize overall costs. Figure 2 displays the results of additional deterministic studies to explore the role of coal cleaning in conjunction with post-combustion emission controls. The results in Figure 2 indicate that for the system configuration using Illinois No. 6 coal, the overall cost of pollution control is minimized when coal cleaning is used to reduce the coal sulfur content by 30 percent below run-of-mine levels (normalized on an energy basis). For subsequent analyses, this least-cost configuration was assumed. For the Pittsburgh seam coal, on the other hand, no coal cleaning proved to be the optimal choice. Although coal cleaning reduces the cost of pollution control at the power plant, the higher cost for the cleaned coal product in this case offset the cost advantage at the power plant.

In addition to applications involving the analysis of a particular technology, another major application of the IECM is for comparing alternative options for a given facility. In particular, the likely cost advantages of advanced process designs relative to conventional technology are of special interest. In the illustrative analysis presented here, the advanced plant design using the copper oxide process is compared to a base-case design employing separate processes for SO_2 and NO_x removal -- a wet limestone scrubber, while NO_x is removed using selective catalytic reduction (SCR), respectively .

Because many of the input parameter distributions are common to both conventional and advanced 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.[1] Therefore, the probability distributions have been determined for the cost *differences* between the copper oxide and FGD/SCR systems using paired samples in which parameters common to each had the same value.

[1] 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.

Table 1: Selected Input Parameter Assumptions for Case Studies

Model Parameter	Nominal Value	Probability Distribution	Values (or s as % of mean)
Emission Constraints			
Nitrogen Oxides	90% Reduction		
Sulfur Oxides	90% Reduction		
Particulates	0.03 lb/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 %		
Economizer Outlet Temp	700 oF		
Preheater Outlet Temp	300 oF		
Financial Parameters			
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	s = 0.06 %

Table 2. 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	0,190	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 Advanced Environmental Control System

Model Parameter	Nominal Value	Probability Distribution	Values (or s 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/m3	Normal	(10 %)
Standard Error, Cu/S Ratio	0	Normal	s = 0.39
Sorbent Attrition	0.06 %	Normal	(41 %)
Ammonia Stoichiometry	(calc)	Normal	(6.25 %)
Regeneration Temp	900 oF	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/ft2	-1/2 Normal	(10 %)
Bag Life	(calc)	Normal	(25 %)
Energy Requirement	(calc)	Normal	(10 %)
Bag Cost	$0.80/ft2	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 %)

[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 ^{o}F.

Figure 3 shows the differences in levelized pollution control costs between the baseline (FGD/SCR) and advanced (copper oxide) systems for two coals and two sulfur recovery options. In all cases, the copper oxide process is most likely to be less expensive and the FGD/SCR system, since cost savings at the 50 percent probability value are positive. However, for the higher sulfur coal there is still a substantial probability (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 difference in 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, indicating a more attractive market potential. 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 in constant 1985 dollars. There is a small probability that the cost savings could be significantly higher.

FUTURE WORK

The preceding discussion was intended to illustrate some of the potential applications of the Integrated Environmental Control Model. During the remainder of this project, emphasis will be placed on developing several additional case studies, and on documenting all aspects of the models currently developed. Version 1.0 of the model recently has been transferred to DOE/PETC along with a draft User's Manual that is currently being expanded and revised. The longer term development of the IECM is expected to involve the addition of more technology modules and greater emphasis on retrofit technologies and costs. To facilitate use of the model, longer term efforts also are expected to focus on the development of a graphical user-friendly interface which would eliminate the need to master the computer command language as now required. A prototype graphical interface developed as part of the current project would serve as a model for this type of future software development. Coupling the IECM with existing DOE databases on power plant and coal characteristics represents another areas for future research.

REFERENCES

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Figure 2. Mean Levelized Pollution Control Cost versus Sulfur Reduction from Coal Cleaning: Copper Oxide/Sulfuric Acid Plant with Illinois #6 Coal

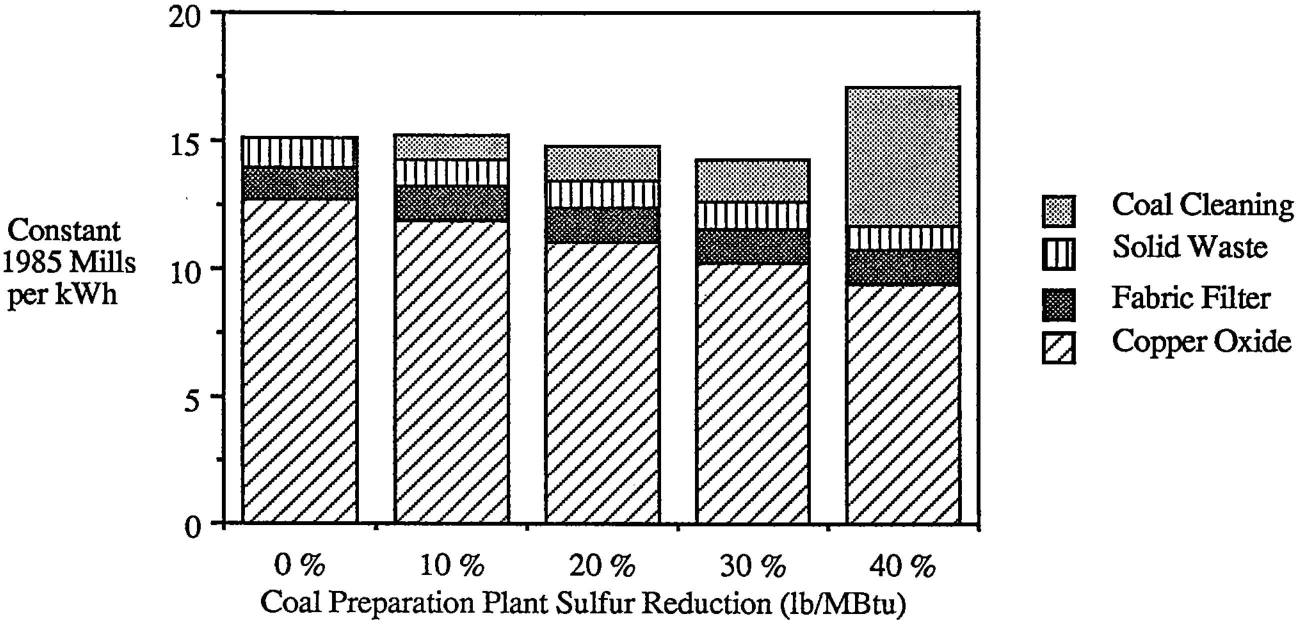

Figure 3. Comparison of Levelized Pollution Control Cost Savings for Copper Oxide vs. FGD/SCR Systems: Effect of Coal and Byproduct Recovery Option