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Modeling IGCC System Performance, Emissions, and Cost Using Probabilistic Engineering Models

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MODELING IGCC SYSTEM PERFORMANCE, EMISSIONS, AND COST USING PROBABILISTIC ENGINEERING MODELS

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ABSTRACT

Integrated gasification combined cycle (IGCC) systems are an emerging technology for the clean and efficient utilization of coal. Because of the close interactions among plant performance, environmental control, and cost, assessments of IGCC technology must be based on integrated analysis of the entire system. The uncertain nature of the limited performance and cost data for the first generation systems, coupled with uncertainties associated with alternative process configurations, suggests a strong need for systematic analysis of uncertainty in evaluating alternative designs or concepts. This paper will present results from a probabilistic case study of one innovative IGCC concept featuring "hot gas cleanup." The case study will demonstrate the new types of insights that can be obtained from probabilistic analysis.

INTRODUCTION

Attempts to predict the commercial performance and cost of technologies that are in early stages of development usually are beset by considerable uncertainty. However, uncertainties are commonly ignored or treated superficially when preparing and interpreting performance and cost estimates. Furthermore, Rand Corporation and others have observed a historical tendency for cost estimates prepared in early stages of technology development to substantially underpredict the actual costs incurred for new technology [1]. Use of such estimates leads to poorly informed decisions, resulting in potentially substantial financial loss.

Integrated gasification combined cycle (IGCC) systems are an emerging technology for clean coal-based power generation. The uncertain nature of the performance and cost of advanced IGCC system concepts suggests a strong need for systematic analysis of uncertainty in evaluating alternative designs. Decisions about research for innovative process concepts and the selection of alternative configurations should be based on explicit and quantitative consideration of the uncertainties which may contribute to the risk of technology failure.

BACKGROUND AND SCOPE OF THIS PAPER

Traditional approaches to handling uncertainties include "sensitivity analysis" and capital cost "contingency factors." However, these approaches are limited and are often inadequate. In practical problems with many input variables which may be uncertain, the combinatorial explosion of possible sensitivity scenarios (e.g., one variable "high", another "low," and so on) becomes unmanageable. Furthermore, sensitivity analysis provides no insight into the *likelihood* of obtaining any particular result. Contingency factors, on the other hand, are often badly under-estimated [2]. Furthermore, the notion of contingency costs is rarely considered explicitly with respect to fixed, variable, or levelized costs.

Predictions about the performance and cost of innovative technologies should reflect the degree of confidence that engineers have in the input assumptions used to generate the predictions. In this research, the approach taken is to explicitly quantify both the range and likelihood of values for parameters used as inputs to the engineering models. Using probabilistic simulation techniques, the simultaneous effect of input parameter uncertainties can be propagated through the model to yield an explicit indication of the uncertainty in output values.

To evaluate advanced coal-based power generation options, a number of IGCC performance models have been developed by the U.S. Department of Energy's Morgantown Energy Technology Center (DOE/METC) [3] using ASPEN, a chemical process simulator [4]. One limitation of ASPEN has been a lack of a capability to analyze uncertainties. Another limitation of the existing IGCC process models has been a lack of directly coupled cost models. To explicitly characterize uncertainties in processes simulated in ASPEN, a general probabilistic modeling capability has been developed and implemented [5]. To evaluate the process economics of selected IGCC systems, new cost models, which estimate capital and annual costs, also have been developed [6]. The present paper describes the application of the new engineering models and probabilistic modeling capability to an evaluation of an advanced IGCC concept under uncertainty.

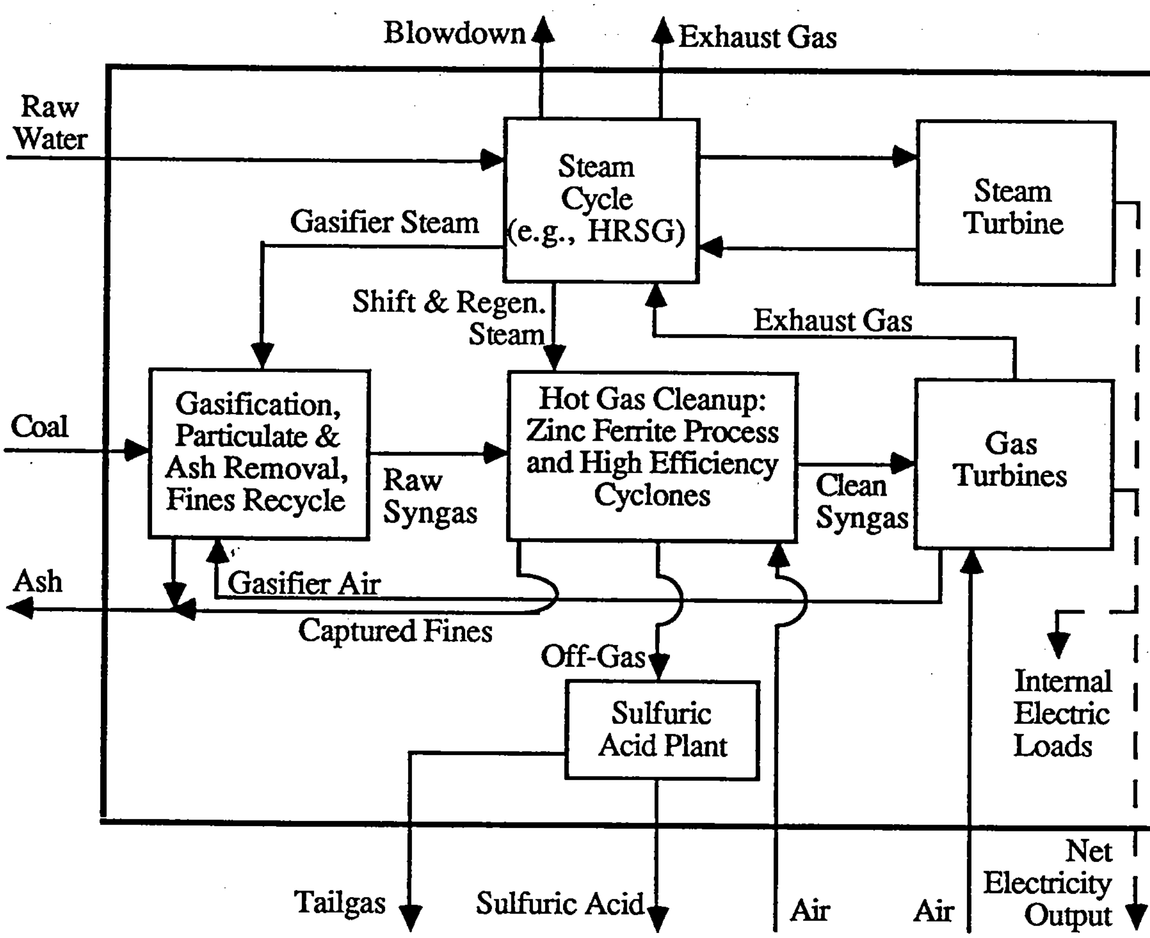

Figure 1. Simplified Schematic of Air-Blown Lurgi-based IGCC with Hot Gas Cleanup

IGCC TECHNOLOGY

A process diagram of an air-blown Lurgi gasifier IGCC system with hot gas cleanup is given in Figure 1. The design basis for this system is a study prepared for METC by General Electric (GE) [7], assuming Illinois No. 6 coal as the fuel. The Lurgi dry-ash gasifier was originally developed in the 1930s and features a counter-current flow of coal past the steam and oxidant feed streams. As a result, the outlet syngas temperature is lower compared to other gasifiers, with an expected temperature of about 1,100 °F for an Illinois No. 6 coal. In a conventional cold gas cleanup design, the syngas would be cooled, resulting in the condensation of oils and tars, which in turn requires expensive process condensate treatment. However, the outlet temperature is an excellent match for the zinc ferrite desulfurization process; therefore, no syngas cooling is required, eliminating the costs and equipment associated with syngas cooling and process condensate treatment. Particulate removal is accomplished with high efficiency cyclones. The zinc ferrite process is expected to reduce the sulfur content of the syngas to 10 ppmv, resulting in low SO_2 emissions from the gas turbine combustor. The sulfur recovered in the zinc ferrite process is sent to a sulfuric acid plant for byproduct recovery. The clean syngas is combusted in an advanced gas turbine combined cycle system with a high firing temperature (2,300 °F) modified to fire low-BTU coal gas.

ENGINEERING MODEL

An engineering cost model was developed based on a review of approximately 30 comprehensive conceptual design studies prepared for DOE, the Electric Power Research Institute (EPRI), and the Gas Research Institute (GRI), as well as other studies which focused on specific process components [6]. The models provide "preliminary" estimates of process capital and operating costs based on the standard method developed by EPRI (1986). To link process flowsheet parameters with economic cost models, the methodological approach was to model all costs at the level of major plant sections. For the Lurgi-based IGCC system, there are approximately a dozen major process sections. The direct capital cost of each process section was estimated separately, based on analytic relationships between direct cost and typical three to five key performance and design parameters. The cost models characterize direct and total capital costs, fixed operating costs, variable operating costs, and the annualized cost of electricity.

The cost model for the IGCC system has been coded into Fortran and implemented as subroutines along with the corresponding ASPEN performance model obtained from METC. The performance models, modified to better estimate gas turbine and zinc ferrite performance and plant discharges [8], determine the key material flow rates and process parameters required by the cost model to calculate capital and annual costs.

CHARACTERIZING UNCERTAINTIES

Uncertainties arise from statistical error, systematic error, variability, and lack of any empirical basis at all for making predictions. The latter is true of concepts for which no testing has been done. The aspects of a process evaluation subject to uncertainty include process performance variables, equipment sizing parameters, process area capital costs, requirements for initial catalysts and chemicals, indirect capital costs, process area maintenance costs, requirements for consumables during plant operation, and the unit costs of consumables, byproducts, wastes, and fuel, to indicate a representative set. Model parameters in any one of these areas may be uncertain, depending on the state of development of the technology, the level of detail of the performance and cost estimate, future market conditions for new chemicals, catalysts, byproducts, and wastes, and so on.

Developing estimates of uncertainty in specific process parameters involves several steps. These include:

- Review the technical basis for uncertainty in the process
- Identify specific parameters that should be treated as uncertain
- Identify the source of information regarding uncertainty for each parameter
- Depending on the availability of information, develop estimates of uncertainty based on:
    - Published judgments in the literature (rarely available)
    - Published information, both quantitative and qualitative, that can be used to infer a judgment about uncertainty
    - Statistical analysis of data
    - Elicitation of judgments from technical experts.

For the Lurgi-based IGCC systems, 47 parameters in the engineering model were characterized probabilistically. While most of these uncertainties were based on data analysis and literature review, approximately one-third of the judgments were elicited from process engineers. These latter judgments were primarily performance uncertainties in the gasification

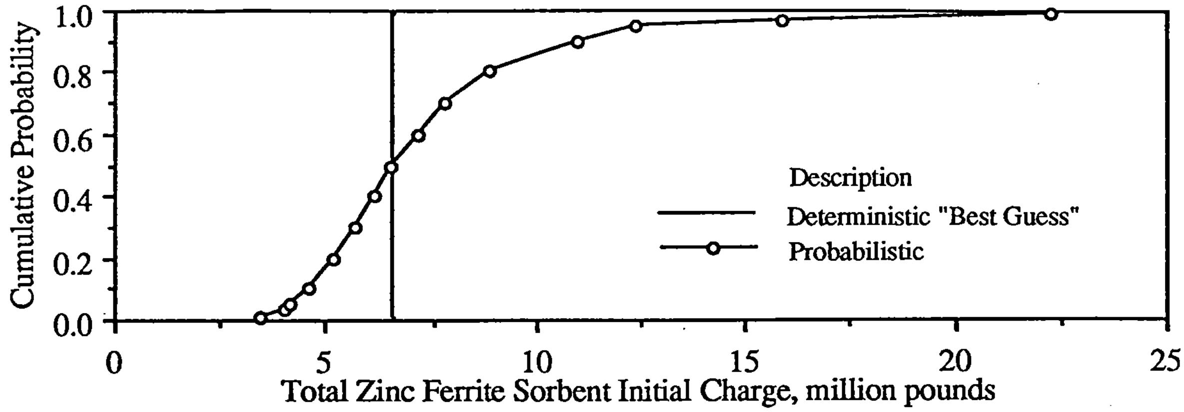

Figure 2. Comparison of Deterministic and Probabilistic Results for the Zinc Ferrite Initial Sorbent Charge.

and zinc ferrite desulfurization process areas. The details of the uncertainty estimates are reported by Frey [8].

RUNNING THE MODELS

The IGCC models were run on a DEC VAXStation 3200 mini-computer using the public U.S. Department of Energy version of ASPEN. A deterministic analysis may take approximately 20 to 30 minutes to run, including input translation and other steps (see MIT [4] for details of ASPEN). In the case of a probabilistic simulation, the flowsheet is executed many times, with a different set of values (samples) assigned to uncertain input parameters each time. Thus, a probabilistic analysis with a sample size of 100 may take 6 to 12 hours to run. However, while stochastic simulation requires an initial computer-intensive phase, the interpretation of results is much easier and more meaningful compared to sensitivity analysis.

MODELING APPLICATIONS AND RESULTS

Several model results are presented which illustrate how the probabilistic approach may be used to characterize uncertainties in key measures of plant performance, emissions, and costs.

Plant Performance

For the Lurgi-based IGCC system with hot gas cleanup, a key performance variable which affects plant costs is the required amount of zinc ferrite sorbent charge. The sorbent charge is a key determinant of the number and size (hence, cost) of the reactor vessels, and the sorbent can represent a significant portion of the capital cost for initial chemicals. The uncertainty in the sorbent charge is shown as a cumulative distribution function (cdf) in Figure 2. The results of a deterministic analysis based on "best guess" values for model inputs is also shown.

The sorbent charge depends strongly on the sorbent sulfur loading capacity. The judgment of a process expert regarding uncertainty in the future commercial-scale sorbent sulfur loading was elicited for this study. The expert indicated that the uncertainty is normally distributed, with a mean (and median) at 17 weight percent. This median value was used also in the deterministic analysis. However, the sorbent charge requirement is a nonlinear function of sorbent sulfur loading [6]. Therefore, the resulting uncertainty in sorbent charge is positively skewed. Thus, while the median sorbent charge is the same as the deterministic "best guess" value at 6.5 million pounds, the mean value is higher, at 7.3 million pounds. Furthermore, in the worst case the sorbent charge could be over a factor of three greater than the deterministic estimate. The use of just deterministic or mean values in a performance estimate would mask the risk a process adopter faces that sorbent charge could be substantially higher.

Plant Emissions

While the zinc ferrite desulfurization system offers the promise of very low SO_2 emissions, IGCC systems with hot gas cleanup may suffer from high NO_x emissions. Thermal NO_x emissions for the air-blown system assumed here are expected to be very low. Fuel NO_x emissions, however, may result from a combination of high fuel gas ammonia content, which

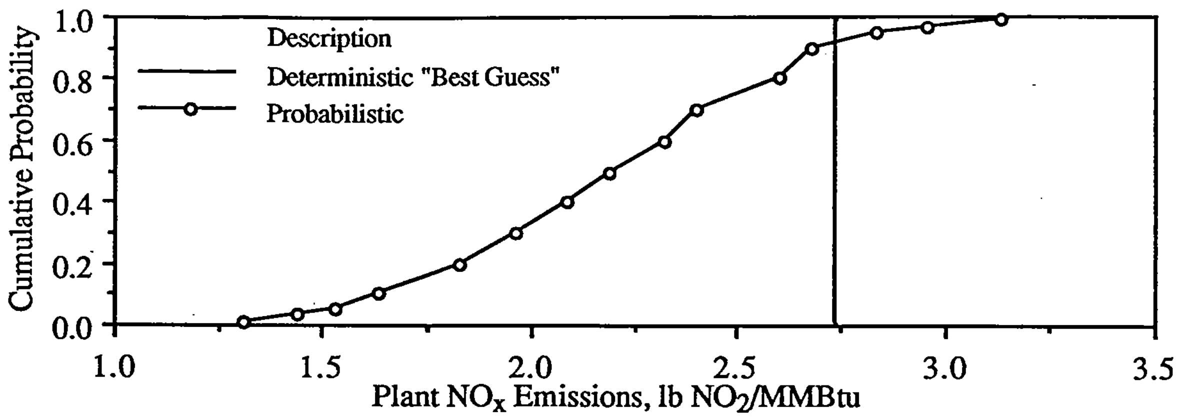

Figure 3. Comparison of Deterministic and Probabilistic Results for NO_x Emissions.

is typical of fixed bed gasifiers, the failure to remove ammonia typical of hot gas cleanup systems, and the conversion of a large portion of the ammonia to NO_x in typical gas turbine combustors. Uncertainties in gasifier ammonia yield and gas turbine ammonia conversion were characterized based on expert elicitation, literature values and discussions with process engineers. Both of these uncertainties were negatively skewed.

The resulting uncertainty in NO_x emissions is negatively skewed. However, the lowest values obtained from the probabilistic simulation are well above current federal new source performance standards for either coal-fired or gas turbine-based power plants. The results imply that there is a strong incentive to develop an efficient control strategy for NO_x emissions. Alternatives under current consideration in the industry include post-combustion selective catalytic reduction (SCR) of NO_x and advanced staged rich/lean combustion techniques to minimize fuel NO_x formation.

Plant Costs

Interactions among uncertainties in plant performance and cost parameters lead to uncertainties in the key measures of cost often used for process evaluation. The levelized cost of electricity is the single most comprehensive measure of plant cost, because it is based on (and sensitive to) all of the factors which affect capital, fixed operating, and variable operating costs. Because it is expressed on a net electricity production basis, it is also sensitive to the plant thermal efficiency. The uncertainty in the cost of electricity is shown in Figure 4.

The risk of poor zinc ferrite sorbent performance is manifested as the long upward tail of the cost uncertainty. The range of uncertainty in the cost of electricity varies by a factor of 2.5 from the lowest to the highest values. In addition, the central values of the probability distribution are higher than the "best guess" estimate. There is approximately a 90 percent probability that the cost of electricity could be higher than the deterministic estimate, due to the interactions of skewed uncertainties and non-linearities in the engineering model. The

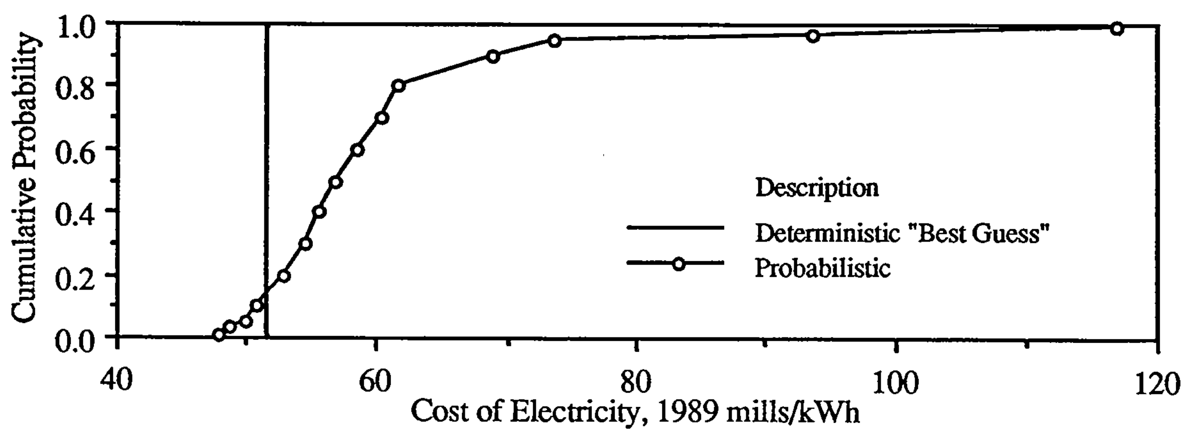

Figure 4. Comparison of Deterministic and Probabilistic Results for the Cost of Electricity.

deterministic estimate includes values of capital cost contingency factors typically assumed in the literature [6]. Yet, it is uncertainties in the variable operating costs that contribute most to the risk of extremely high levelized costs. These risks can be reduced significantly, however, through a program of targeted R&D identified in separate analyses [8].

OTHER APPLICATIONS

Other applications of the probabilistic evaluation method not discussed here include: (1) comparison of design trade-offs under uncertainty; (2) evaluation of the reductions in uncertainty that may be obtained from further process research; (3) evaluation of alternative judgments regarding model parameter uncertainties by different experts as they affect model results; (4) evaluation of the importance of correlation structures in model parameter uncertainties; (5) comparative analysis of competing technologies under uncertainty; and (6) the use of decision analysis techniques to interpret modeling results. These types of applications are discussed by Frey [8].

CONCLUSIONS

While traditional approaches to technology evaluation inadequately account for uncertainties and lead to over-optimistic estimates of performance and cost, the probabilistic evaluation method advanced here permits explicit characterization of the uncertainties in performance, emissions, and cost estimates. Furthermore, the "surprises" that often account for "cost growth" can be captured by the use of sufficiently detailed engineering models coupled with specification of uncertainties in specific model parameters. Thus, probabilistic modeling is an important technique for developing realistic estimates that are needed for research planning and technology selection.

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