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CHARACTERIZING UNCERTAINTIES IN IGCC SYSTEM PERFORMANCE AND COST

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OBJECTIVES

The objective of this research is to develop, implement, and demonstrate a capability for evaluating performance and cost uncertainties in integrated gasification combined cycle (IGCC) systems. While traditional approaches to technolo-gy modeling and decision making may be appro-priate for well-established, commercial technology, they are inadequate as a basis for research planning for technologies in early stages of research and development. A probabilistic evaluation method-ology, and the required software capabilities, are developed for the ASPEN simulator. The method is applied to detailed case studies.

BACKGROUND INFORMATION

Nearly all analyses of energy and environmental control technologies that are in early phases of research involve uncertainties. According to the Rand Corporation (Hess and Myers, 1989):

> Accurate assessment of the costs of advanced technologies has always been one of the most difficult and uncertain tasks facing an R&D planner .

Predictions of the future commercial-scale performance of a new technology are often based on limited experimental data from small-scale testing. Predictions of future cost are typically expressed as deterministic point-value estimates based on assumed values of key performance and design variables, without regard to their uncertainty. Such performance and cost estimates of a new technology, however, are inherently uncertain because of the lack of large-scale experience to verify expectations.

Rand and others have identified a systematic tendency for the performance of advanced process technologies to be over-estimated and for costs to be under-estimated. Misleading estimates of the performance and cost of new processes can have deleterious implications for research planning and the allocation of resources to the development of alternative technologies.

Explicit characterization of uncertainty in process performance and cost is postulated as a key feature of a robust research planning method. A number of motivating questions for such a research planning method include:

- What is the expected commercial performance and cost based on what is currently known?
- How reliable are performance estimates for mature, commercial plants?
- How do variations in design affect cost?
- What are the key factors driving uncertainty in performance and cost?
- What are the risks and pay-offs of a new technology compared to conventional technology?
- What are the expected results from further research, development, and demonstration (RD&D)?

PROJECT DESCRIPTION

In this research, a systematic quantitative method is developed and applied to answer the questions above. The key features of the research planning method are summarized in Table 1.

To develop a probabilistic method for technology evaluation and research planning, work under this contract has focused on three major tasks. Task 1 was the development of a probabilistic modeling framework for the ASPEN chemical process simulator (Rubin and Diwekar, 1989). This generalized capability can be used to evaluate uncertainties in any process technology which can be modeled in the ASPEN simulator.

Task 2 involved the development of technology-specific performance and cost models for IGCC systems. This work utilized performance models for several IGCC systems already developed by the Morgantown Energy Technology Center (METC) using ASPEN. However, a limitation of those models has been the lack of directly-coupled cost models, which has prevented the simultaneous evaluation of process performance and economics in a single simulation. To address this shortcoming, new cost models, which estimate capital, annual, and levelized costs, have been developed (Frey and Rubin, 1990).

Finally, Task 3 demonstrated the use of the probabilistic evaluation methodology via a series of probabilistic case studies involving advanced and conventional IGCC system designs. The results of this effort were especially directed at application for R&D planning and management (Frey and Rubin, 1991).

Table 1. Procedure for Probabilistic Analysis

1. Identify set of candidate technologies
2. Identify decision criteria (e.g., cost)
3. Using criteria, select a subset of technologies for detailed evaluation
4. Develop engineering performance and cost models for each screened candidate.
5. Identify uncertain parameters in engineering models.
6. Identify sources of information about uncertainty for each parameter:
    - Data
    - Literature
    - Technical experts
7. Characterize Uncertainty in Parameters
    - Statistical analysis
    - Expert elicitation
8. Implement models and parameter uncertainties in a probabilistic modeling environment (e.g., ASPEN)
9. Analyze results:

- Statistical techniques (e.g., partial correlations)
- Cumulative distribution functions (cdf's)
- Probabilistic sensitivity analysis
- Probabilistic screening analysis

10. Apply approach to:
    - Characterize uncertainties in key measures of plant performance, emissions, and cost
    - Analyze process design
    - Identify research priorities
    - Assess and compare risks

RESULTS

This paper will focus on the methodology and modeling applications of Task 3. Case studies are presented which illustrate the types of insights that are obtained from probabilistic analysis.

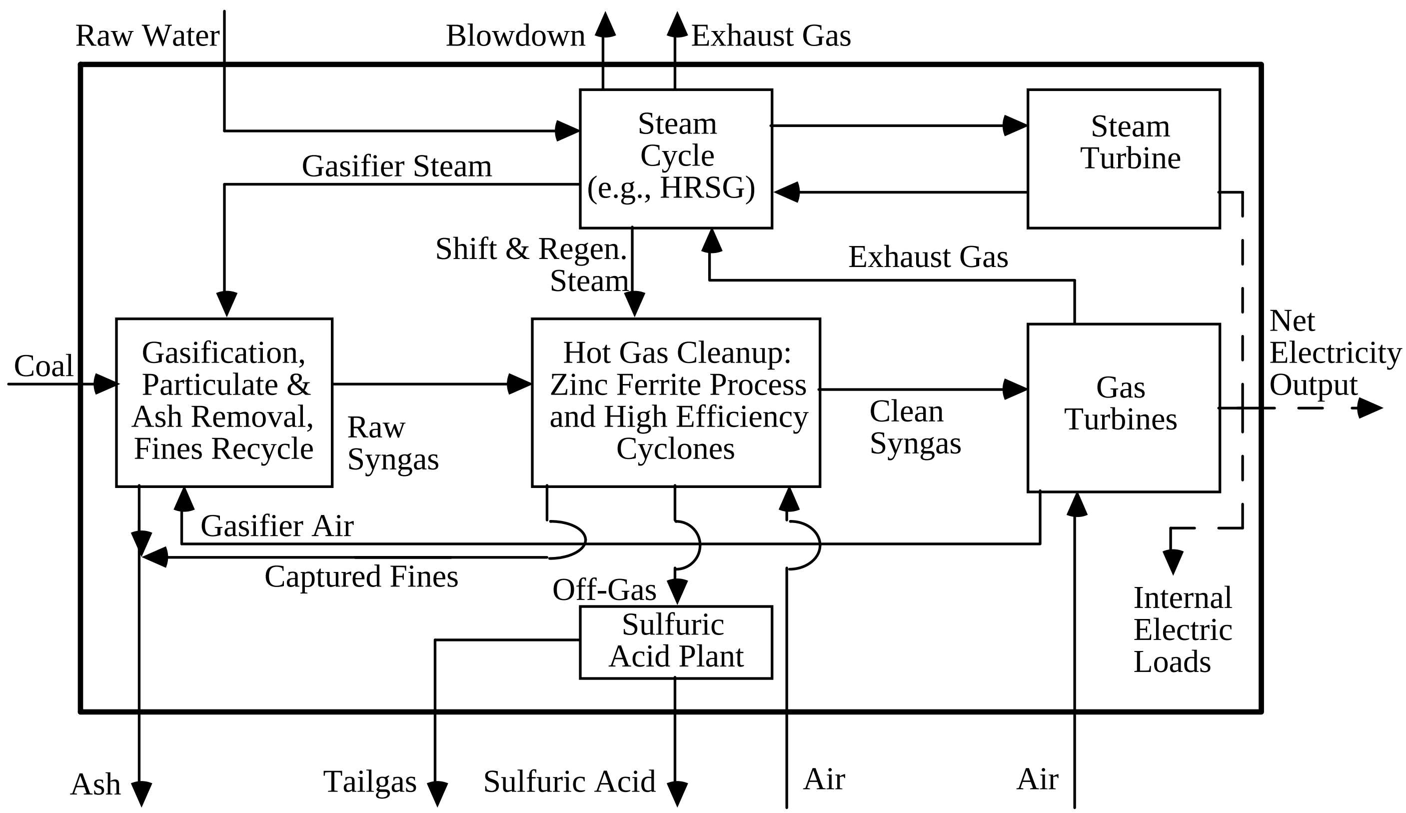

Figure 1. Schematic of Air-blown Dry-Ash Lurgi Gasifier IGCC System with Hot Gas Cleanup

Selecting Technologies for Evaluation

The probabilistic evaluation method is applied to detailed case studies of two IGCC systems. These systems include an oxygen-blown fluidized bed gasifier design with cold gas cleanup (representative of conventional designs) and an air-blown Lurgi gasifier design with hot gas cleanup (representing an advanced design). The advantages of the "simplified" Lurgi-based IGCC system are that: (1) it does not require an expensive and energy-consuming oxygen plant; (2) it eliminates the capital costs associated with fuel gas cooling; and (3) it eliminates the energy penalties associated with fuel gas cooling. A process diagram of the Lurgi IGCC system is given in Figure 1.

Engineering Models

Performance models of these systems were previously developed by METC. These models were modified for use in this study to more completely characterize performance and emissions. Newly developed cost models have been directly coupled to the performance models. The cost models are based on approximately 30 design studies of IGCC systems. Direct capital costs are estimated for 10 to 12 major process areas for each IGCC system. Typically, several performance and design variables are included in the direct cost models. Indirect capital costs are estimated based on approximately 60 cost model parameters. Fixed and variable operating costs are estimated based on 40 to 50 parameters. Total levelized costs are also calculated. All cost models are documented in Frey and Rubin (1990).

Characterizing Uncertainties

Predictions about the performance and cost of new technologies should reflect the degree of confidence that engineers have in the input assumptions used to generate the predictions. Using probabilistic simulation techniques, the effect of simultaneous input parameter uncertainties can be propagated through the engineering model to yield an explicit indication of the uncertainty in output values.

There are a number of types of uncertainty that an analyst faces in trying to predict the commercial-scale performance and cost of a new process technology. These include statistical error, systematic error, variability, and lack of an empirical basis for concepts that have not been tested. Uncertainties may apply to different aspects of the process, including 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. 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 estimates, future market conditions for new chemicals, catalysts, byproducts, and wastes, and so on.

It may not always be possible to develop estimates of uncertainty based on classical statistical analysis, nor would such an approach be appropriate in many cases. Particularly for new process technologies, data may be lacking regarding the sources of uncertainty that a process engineer or analyst knows to exist. Thus, data analysis alone would be an insufficient basis for estimating uncertainty in a variable. When data are lacking, estimates of uncertainty must rely on the informed judgments of technical experts. Judgments regarding uncertainties can be encoded as probability distributions, using techniques discussed elsewhere (Frey and Rubin, 1991).

For the two IGCC systems of interest, uncertainties in specific performance and cost parameters were explicitly characterized using probability distributions. Estimates of uncertainties were based on literature review, data analysis, and elicitation of expert judgments from METC process engineers involved in technology development.

The characterization of performance uncertainties focused on three major process areas: gasification; zinc ferrite desulfurization; and gas turbine. Uncertainties in additional cost model parameters also were characterized, including direct and indirect capital costs, operating and maintenance costs, financial assumptions, and unit costs of consumables, byproducts, and wastes.

Technical experts at METC were approached for their judgments regarding uncertainties. Because the expertise of the METC experts was strongly performance-oriented, and less cost-oriented, the focus of the uncertainty elicitations was on performance. For each of the three major process areas, a briefing packet was developed and distributed to several METC experts. The packet consisted of three parts: (1) a 9 page introduction to uncertainty analysis; (2) a 10-20 page technical background paper on the process area of interest, with focus on specific aspects that may be uncertain; and (3) a written questionnaire asking for uncertainty judgments for specific model parameters. After the questionnaires were returned, a follow-up phone interview was used to clarify responses.

Expert judgments regarding most performance uncertainties were successfully elicited using this approach. Each expert is referred to here by arbitrary designations. The two gasifier experts are LG-1 and LG-2. The three zinc ferrite experts are ZF-1, ZF-2, and ZF-3. While qualitative responses were obtained from two gas turbine experts, insufficient information was reported to develop probability distributions for the parameters in the questionnaire.

A few examples of the expert responses are given here. One parameter in the Lurgi gasification process area which affects plant performance is the coal fines carryover from the gasifier into the exiting raw fuel gas. In the design assumed here, 30 percent of the coal feed, on a weight basis, consists of coal fines less than 1/4 inch in size. There is uncertainty regarding what portion of the coal fines may simply pass through the gasifier into the exiting raw gas without conversion. The judg-ment of Expert LG-1 regarding uncertainty in gasifier fines carryover is shown graphically in Figure 2. The expert indicated that the uncertainty in coal fines carryover is positively skewed toward high values, with carryover likely to be 3.5 to 5 percent of the coal feed rate.

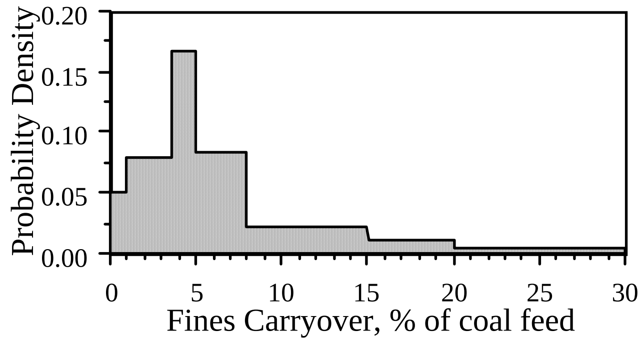

Figure 2. Judgment of Expert LG-1 For Uncertainty in Gasifier Fines Carryover

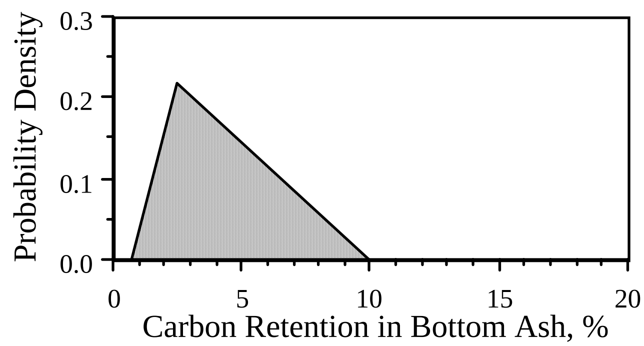

Figure 3. Judgment of Expert LG-1 For Uncertainty in Gasifier Carbon Retention

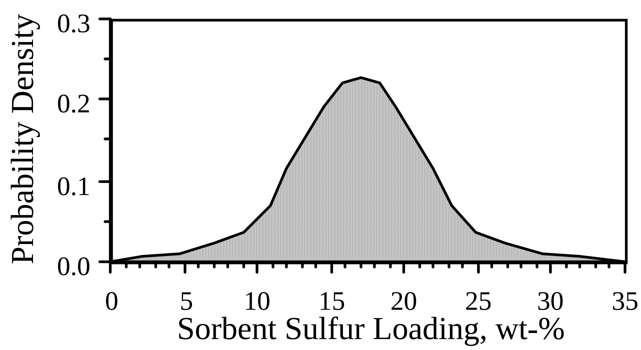

Figure 4. Judgment of Expert ZF-1 For Uncertainty in Sorbent Sulfur Loading

Expert LG-1 also provided a positively skewed judgment regarding uncertainty for gasifier bottom ash carbon retention, as shown in Figure 3. High carbon retention might be associated with poor distribution of gas flow, while low retention would be associated with good process control, smooth operations, and a properly operated grate.

Expert ZF-1 estimated a symmetric normally distributed uncertainty in the zinc ferrite sorbent sulfur loading capacity, as shown in Figure 4. High sorbent loadings would be associated with an ideal reactor, and no sorbent deactivation, while low values would be associated with gas flow channeling in the sorbent bed and sorbent deactivation.

For uncertain parameters for which expert judgments could not be obtained from METC personnel, the authors supplied their own judgments based on literature review, data analysis, and discussions with industry experts. A total of 47 parameters were treated probabilistically in the Lurgi case study. The basis for all uncertainties used in these analyses is given in Frey and Rubin (1991).

Modeling Applications

Case studies of the Lurgi-based system illustrate how probabilistic analysis is used to characterize uncertainties in measures of plant performance and cost; identify and prioritize key uncertainties; evaluate design trade-offs under uncertainty; and identify strategies for further research. Moreover, competing technologies are compared probabilistically to evaluate the likelihood of the advanced technology having better performance and lower cost than conventional technology. The results reported here are based on a plant size of approximately 650 MW using Illinois No. 6 coal.

Running the Models. The IGCC models were run on a DEC VAXStation 3200 mini-computer using the public version of ASPEN with the new stochastic modeling capability (Rubin and Diwekar, 1989). A deterministic analysis may take approximately 20 to 30 minutes to run, including input translation and other steps. For 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.

Uncertainties in Model Outputs. The engineering models were exercised in the probabilistic modeling environment to characterize uncertainties in key measures of plant performance and cost, based on the uncertainties assigned to model input parameters.

Estimates of plant thermal efficiency are shown in Figure 5. The deterministic value, based on "best guess" assumptions for model input parameters, is 38.5 percent. However, from the probabilistic simulation, the median (50th percentile) value of efficiency is only 37.7 percent, and the mean (average) value is even lower at 37.5 percent. The probability distribution is negatively skewed, with a long tail below the 10th percentile. Efficiency could be less than 35.9 percent, and may go as low as 32 percent. There is only about a 20 percent chance that efficiency would be higher than the deterministic estimate, and it could go as high as 40 percent.

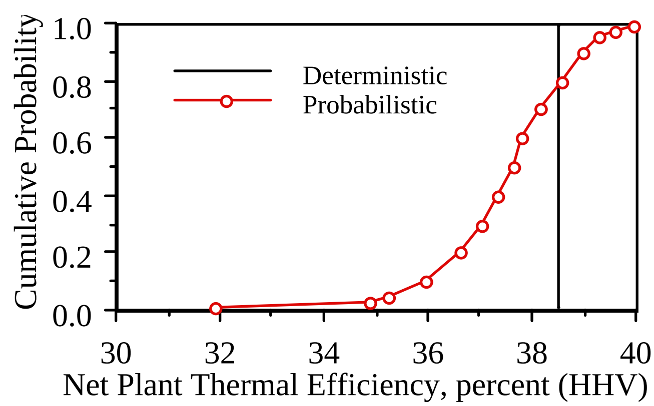

Figure 5. Uncertainty in Plant Efficiency

The negative skewness of the uncertainty in plant thermal efficiency results from the assumptions regarding input uncertainties. For example, Expert LG-1, who provided the gasifier judgments in this example, indicated that the most likely value for coal carbon retention in the bottom ash of the gasifier was 2.5 percent of the carbon in the coal feed. This value was used as the deterministic estimate. However, this expert also indicated that the carbon retention could be as low as 0.75 percent, or as high as 10 percent (see Figure 3). Carbon retained in the bottom ash represents a significant efficiency penalty on the IGCC system, because it is not combusted in the gasifier nor converted to fuel gas. Thus, the positively skewed assumption regarding uncertainty in carbon retention is a major factor contributing to the negatively skewed uncertainty in plant thermal efficiency.

The zinc ferrite sorbent charge depends strongly on the sorbent sulfur loading capacity. Expert ZF-1 indicated that the uncertainty is symmetrically distributed, with a mean (and median) at 17 weight percent. This median value was used in the deterministic analysis. However, the sorbent charge requirement is a nonlinear function of sorbent sulfur loading (see Task 2 Topical Report). Therefore, the resulting uncertainty in sorbent charge is positively skewed (see Figure 6). 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 more than three times the deterministic estimate. Thus, use of only a deterministic or mean value in a performance estimate masks the risk that sorbent charge could be substantially higher.

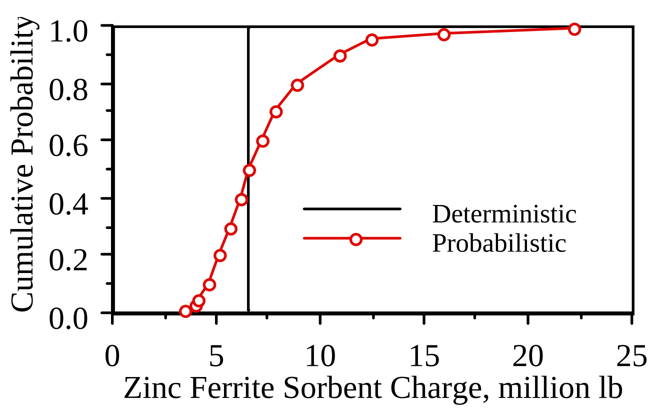

Figure 6. Uncertainty in Sorbent Charge

Interactions among uncertainties in plant performance and cost parameters lead to uncertain-ties in key measures of cost used for process evaluation. As shown in Figure 7, the uncertainty in the total plant capital cost covers a wide range, from about $1,200/kW to over $1,800/kW. The mean and median, both approximately $1,465/kW, are higher than the deterministic estimate of $1,410/kW. There is almost a 70 percent chance that the capital cost would be higher than the "best guess" estimate, which includes so-called "contingency" allowances intended to account for both performance- and project-related uncertainties. In the probabilistic estimate, contingency factors are replaced with explicit representations of uncertainty in direct costs. Figure 7 suggests that use of the deterministic cost estimate would expose a decision-maker to a substantial chance of a cost overrun.

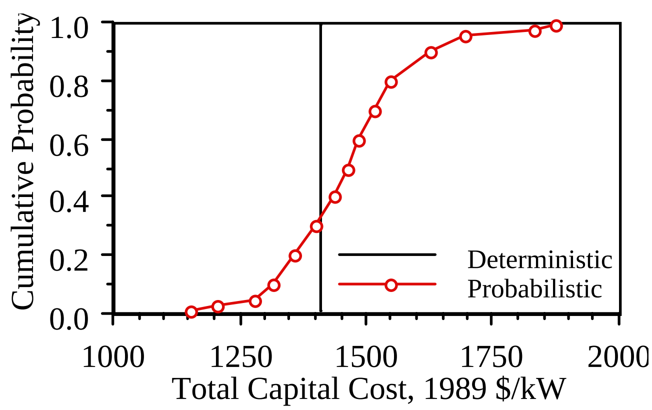

Figure 7. Uncertainty in Capital Cost

The levelized cost of electricity (COE) 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 COE is shown in Figure 8.

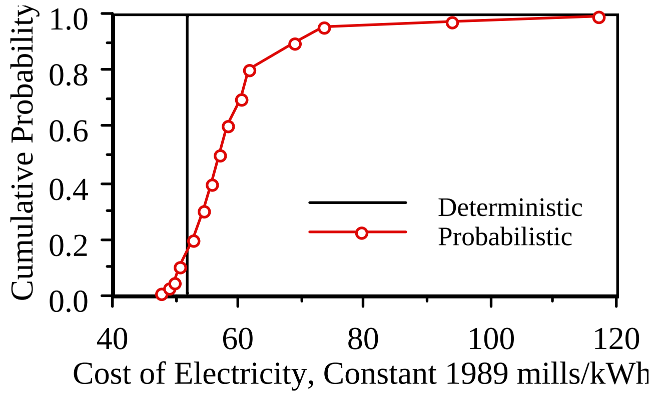

Figure 8. Uncertainty in Levelized Total Cost

The risk of poor zinc ferrite sorbent performance is manifested in the long upward tail of the cost uncertainty. The range of uncertainty in the COE 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 COE could be higher than the deterministic estimate, due to the interactions of skewed uncertainties and non-linearities in the engineering model. 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 (see Frey and Rubin, 1991).

Key Uncertainties. Using statistical tech-niques, the key input uncertainties that drive uncertainty in performance and cost can be identified and prioritized for further research. Key input uncertainties that affect uncertainty in the COE are shown in Table 2. These include both performance and cost parameters in the zinc ferrite, gas turbine, and gasifier process areas. Thus, simultaneous interactions among several process areas are shown to be important here.

Table 2. Key Input Uncertainties for Levelized Total Cost

1. Zinc Ferrite Sorbent Attrition Rate
2. Zinc Ferrite Sorbent Sulfur Loading
3. Gasifier Coal Throughput
4. Gas Turbine Direct Capital Cost
5. Gasifier Maintenance Cost
6. Project-Related Indirect Costs
7. Zinc Ferrite Sorbent Unit Costs
8. Gasifier Direct Capital Cost

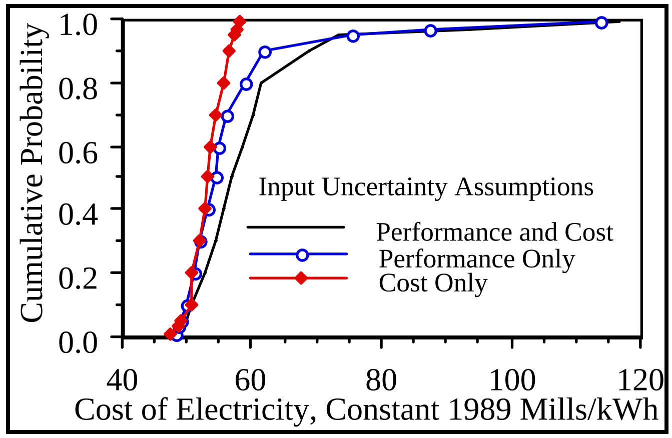

Figure 9. Sources of Uncertainty in Levelized Total Cost

The interactions among uncertainties can also be illustrated graphically. Figure 9 shows the uncertainty in the COE resulting from performance or cost uncertainties only, and from the combined interactions simultaneously. Performance-related uncertainties are clearly shown to be the source of the extreme positive skewness in the total cost.

Probabilistic Design Analysis. One process development that is being sought by DOE and others is a low pressure drop fuel valve for IGCC gas turbine applications. Fuel valve pressure drop represents an energy penalty to the IGCC system, because gasifier blast air must be pressurized to overcome the pressure drop between the gasifier and the gas turbine combustor. An IGCC system with a low pressure drop (20 psi) fuel valve was compared to one with a conventional fuel valve (70 psi pressure drop, representative of the MS7001F gas turbine). Dif-ferences in gas turbine cost, if any, associated with the advanced fuel gas valve are not considered.

The 50 psi reduction in pressure drop between the gasifier exit and the gas turbine combustor results in a mean efficiency savings of 0.8 percentage points, which lowers cost. However, the overall effect of the reduced pressure drop on process costs is more complex. The gasifier coal throughput is a function of gasifier pressure. As pressure is reduced, the gasifier coal throughput is reduced. Therefore, more gasifier vessels, which are of a standard size, must be utilized to accommodate the total coal flow. Furthermore, as system pressure is reduced, the fuel gas volumetric flow rate increases. This results in increased costs due to increased vessel size requirements for the cyclone and zinc ferrite process areas.

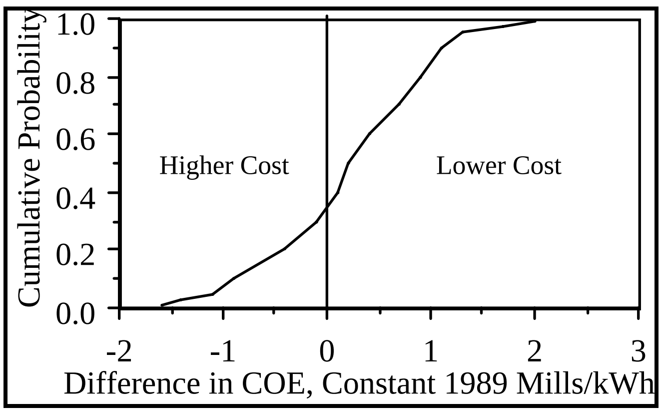

Figure 10. Cost Savings from New Fuel Valve

The combined effect of these trade-offs is shown in Figure 10, which shows a probability distribution for the *difference* in levelized cost between the systems with the advanced and conventional fuel valves. A positive number indicates that the advanced fuel valve reduces levelized cost (as desired). The calculated mean cost savings is 0.2 mills/kWh. However, there still is a 35 percent chance that the overall cost will be higher with the new valve. This is because of the possibility that the increased costs associated with larger or more numerous process vessels will offset the cost savings associated with higher plant efficiency.

Additional Research. Additional research is likely to reduce the uncertainties in specific process performance and cost parameters. To illustrate this point, reduced uncertainties in key parameters for three major process areas are assumed. The "reduced" uncertainties assume no changes in the central values or skewness of the parameter; the only change is in the range of possible values.

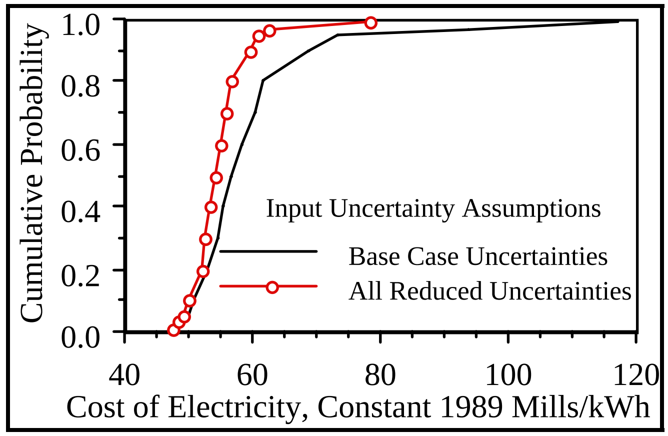

Figure 11. Reducing Uncertainty in Total Cost

The effect of reducing uncertainties in specific performance and cost parameters on the cost of electricity is shown in Figure 11. Reduction in uncertainties in the zinc ferrite process area leads to a substantially smaller tail at the upper end of the distribution. Reductions in other uncertainties (e.g., gasifier-related) also reduce the central values of the distribution. Thus, reduced input uncertainties decrease both the mean cost and the risk associated with high cost outcomes.

Multiple Experts. In many cases, there may be more than one expert whose judgment could be obtained to estimate uncertainties. In our IGCC studies, several experts provided judgments for the gasification and zinc ferrite process areas. The implications of these alternative judgments for the zinc ferrite process area are briefly discussed.

Judgments from three people were obtained, with one expert, ZF-2, providing two sets of judgments. One set, ZF-2P, were based on the use of high efficiency cyclones for particulate control, while the other set, ZF-2R, were based on barrier filtration and an upstream chloride guard. Four cases were run in which all IGCC uncertainties were fixed except for differences among the zinc ferrite experts. The results are compared in Figure 12.

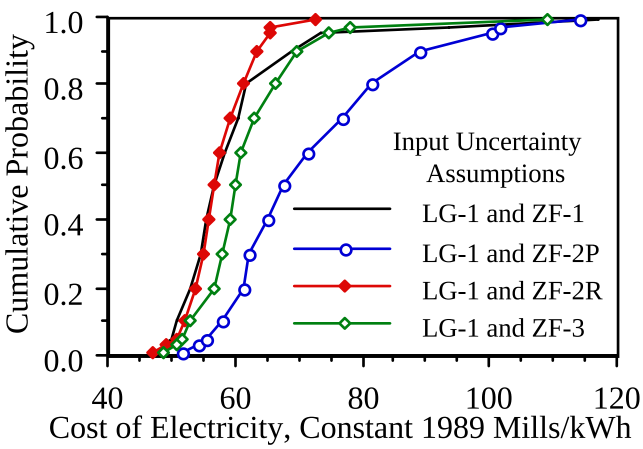

Figure 12. Comparing Zinc Ferrite Experts

Three sets of results are relatively close with respect to central values of the distributions. Three sets also indicate a probability of very high costs. Only the set based on ZF-2R indicate that costs can be contained within a relatively short upper tail.

Do the experts agree? There appears to be reasonable agreement among three of the cases. However, differences among them are attributable to the complex interactions among assumptions that affect the sorbent charge requirement and makeup sorbent. Specific input parameters can be identified and targeted for further investigation to reduce disagreements that prove critical to R&D decisions.

Comparison to Other Technology. The preceding sections have focused on case studies of an individual IGCC technology. In this section, the advanced Lurgi-based system is compared probabilistically to a more conventional IGCC design. In cases where uncertainties are common to both systems (e.g., ash disposal cost), the comparison takes into account the underlying correlation structure.

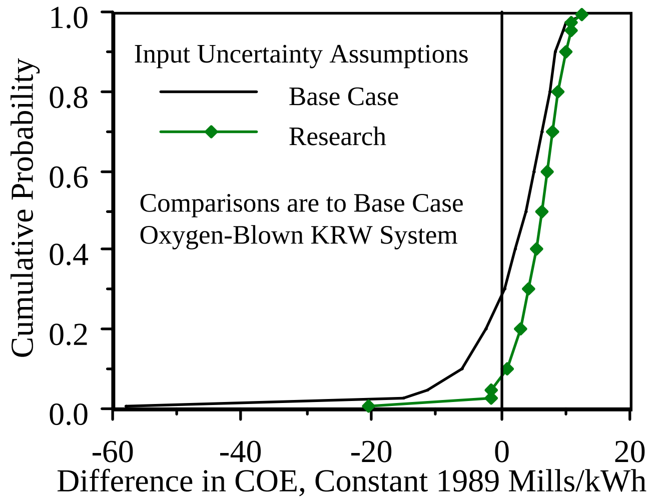

Figure 13. Savings from New Technology

The probability distribution for the cost savings between the advanced and conventional IGCC systems is shown in Figure 13. There is an estimated 73 percent probability that the new technology will be less expensive than the conventional one by about 5.5 mills/kWh (or roughly 10 percent). Conversely, there is a 27 percent chance the new technology could be more expensive by about 9.5 mills/kWh, due primarily to cost growth in the zinc ferrite process area. Overall, the mean savings is 1.5 mills/kWh.

Additional research could change this result, primarily by reducing the risks of the zinc ferrite process. Illustrative research results for three major process areas would increase the probability of cost savings to over 90 percent, and increase the overall mean savings to about 6 mills/kWh. Similar results are obtained even if research simultaneously reduces uncertainties in the conventional technology.

Discussion

Compared to deterministic analysis, the probabilistic modeling approach requires that more detailed judgments be made regarding the values assigned to performance and cost parameters in an engineering model. The time required to develop estimates of uncertainty is usually higher than the time that would be required to make a "best guess" estimate. However, by systematically thinking about uncertainties in specific parameters, an analyst is more likely to uncover potential sources of cost growth or performance shortfalls that are historically overlooked in engineering analyses of new technologies.

As shown in many of the case studies, the influence of skewed distributions on model results can be important. They tend to shift the central tendency of resulting uncertainties in performance and cost, and can lead to long tails representing unfavorable outcomes. These types of interactions cannot be evaluated systematically in deterministic analysis. Thus, while the information require-ments may be more demanding for probabilistic analysis, the benefit is more realistic estimates of performance and cost. Thinking about uncertainties is an important way to gain understanding into the key factors that drive the risk of failure.

Conclusions

An integrated performance and cost model of the Lurgi-based IGCC system has permitted the evaluation of interactions involving the gasifi-cation, hot gas cleanup, and power generation pro-cess areas that affect performance, emissions, and cost. The explicit characterization of uncertainty provided critical insights that could be overlooked in deterministic analyses.

It was found that the Lurgi system examined here may incur high zinc ferrite sorbent replacement costs associated with potentially poor sorbent performance interacting with other process uncertainties. However, reducing uncertainties in key parameters in the gasifier and zinc ferrite process areas will substantially reduce the downside risks and increase the expected pay-offs, *even if conventional technology also improves*. Thus, the modeling results indicate that risks of lower efficiency and higher variable operating costs can be isolated to a few key parameters which can become the focus for further research.

Probabilistic modeling is shown here to be a versatile tool for technology evaluation, cost estimating, process design, risk assessment, research planning, and technology selection. By forcing process developers and evaluators to consider uncertainties explicitly (rather than ignore them), probabilistic engineering models can help improve research planning and management by allowing the implications of uncertainties to be thoroughly evaluated.

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