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PROCESS ENGINEERING AND DESIGN

Evaluation of Advanced Coal Gasification Combined-Cycle Systems under Uncertainty

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Advanced integrated gasification combined cycle (IGCC) systems have not been commercially demonstrated, and uncertainties remain regarding their commercial-scale performance and cost. Therefore, a probabilistic evaluation method has been developed and applied to explicitly consider these uncertainties. The insights afforded by this method are illustrated for an IGCC design featuring a fixed-bed gasifier and a hot gas cleanup system. Detailed case studies are conducted to characterize uncertainties in key measures of process performance and cost, evaluate design trade-offs under uncertainty, identify research priorities, evaluate the potential benefits of additional research, compare results for different uncertainty assumptions, and compare the advanced IGCC system to a conventional system under uncertainty. The implications of probabilistic results for research planning and technology selection are discussed.

Introduction

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 overestimated and for costs to be underestimated (Merrow et al., 1981). Misleading estimates of the performance and cost of new processes can have deleterious implications for research planning and the allocation of

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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 the following:

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

IGCC Technology

Integrated gasification combined cycle (IGCC) systems are an emerging technology for cleaner and more efficient use of coal for power generation. These systems feature conversion of coal to a fuel gas by reaction with steam and oxygen in a pressurized reducing atmosphere; cleanup of the fuel gas to remove particulates, sulfur compounds, and other contaminants; and combustion of the fuel gas in a gas turbine combined-cycle system. IGCC systems are capable of higher thermal efficiency and lower gaseous, liquid, and solid discharges than conventional pulverized-coal-fired power plants (Pietruszkiewicz et al., 1988). However, few IGCC systems have been commercially demonstrated. Those that have been demonstrated feature entrained-flow gasifiers using "cold" (100 °F) wet fuel gas cleanup technology (Cool Water, 1988; Hager and Heaven, 1990). For many other IGCC concepts that are in early stages of development, there are uncertainties regarding process performance, emissions, and cost that may not be resolved until a commercial-scale demonstration plant is built. Uncertainties are particularly important for many advanced concepts featuring high-temperature "hot" (e.g., 1000 °F) dry fuel gas cleanup technology. Hot gas cleanup offers the potentially key advantages of higher plant thermal efficiencies and lower costs due to the elimination of fuel gas cooling and associated heat exchangers (Bajura, 1989).

Analysis Method

A systematic, quantitative method is developed and applied to answer the questions posed above. The key features of the research planning method are summarized in Table I.

Table I. 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:
    - laboratory or plant 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

The key features of the method include (1) the development of a consistent set of engineering performance and cost models for each technology to be evaluated, (2) the characterization of uncertainties in specific parameters of the engineering models, (3) application of the models in a probabilistic modeling environment to characterize uncertainties in model outputs, and (4) analysis of model results for the purposes of technology evaluation and research planning (Frey, 1991).

Uncertainties in specific input parameters of the IGCC engineering models are characterized on the basis of data analysis, literature review, or the elicitation of judgments from process engineers. To represent uncertainties in any process technology, a probabilistic modeling capability has been added to ASPEN (Rubin and Diwekar, 1989). This capability utilizes a Fortran program developed by Iman and Shortencarier (1984) which uses either random Monte Carlo or Latin hypercube sampling to assign probability distributions to process model parameters and to generate samples from those distributions. A Fortran program developed by Iman, Shortencarier, and Johnson (1985) is also employed for analysis of probabilistic simulation results. This latter program has options for either sample or rank partial correlation coefficients (PCC) and standardized regression coefficients (SRC) to measure the linear or nonlinear dependence of model output uncertainties on input uncertainty assumptions. The probabilistic modeling capability has been implemented into ASPEN through a new unit operation block and associated Fortran blocks.

This paper focuses on demonstration of the probabilistic evaluation methodology via a series of probabilistic case studies involving advanced and conventional IGCC system designs. The results of this effort are especially directed at application for research and development (R&D) planning and management (Frey and Rubin, 1991). We illustrate such applications through the set of case studies described below.

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 and an air-blown fixed-bed dry-ash (e.g., Lurgi) gasifier design with hot gas cleanup. The former is representative of conventional design practice with respect to gas cleanup, although many near-commercial IGCC concepts feature entrained-flow, rather than fluidized-bed, gasifiers. The latter is representative of advanced concepts for gas cleanup. 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 advanced IGCC system is given in Figure 1. The U.S. Department of Energy (DOE) has sponsored system studies, and process research and development, on this and related IGCC systems (Corman, 1986; Haldipur et al., 1988; Bissett and Strickland, 1991). The advanced IGCC technology is evaluated here with respect to plant efficiency, emissions, capital cost, and levelized cost of electricity.

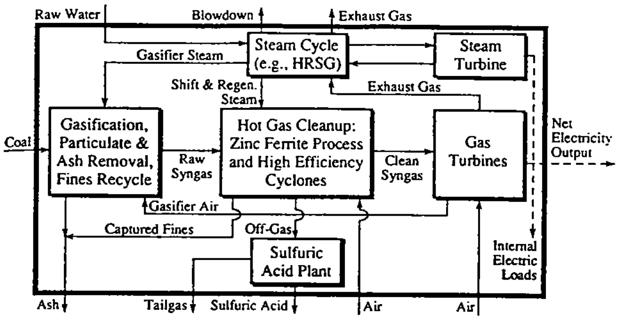

Figure 1. Schematic of air-blown dry-ash fixed-bed gasifier IGCC system with hot gas cleanup.

Engineering Models. Performance models of these systems were developed previously by DOE's Morgantown Energy Technology Center (METC) using the ASPEN chemical process simulator (e.g., Stone, 1985). These models were modified for use in this study to more completely characterize gas cleanup and gas turbine performance and emissions (Frey, 1991). Newly developed cost models have been directly coupled to the performance models (Frey and Rubin, 1990). The cost models were developed based on approximately 30 design studies of IGCC systems. Direct capital costs are estimated for 10–12 major process areas for each IGCC system. Typically, several performance and design variables are included in the direct cost models. Indirect and other capital costs are estimated based on approximately 60 cost model parameters. These include process area contingencies, project contingency, indirect construction costs, sales tax, allowance for funds used during construction, environmental permitting costs, spare parts inventory costs, costs for initial inventories of fuels and chemicals, land cost, and startup costs. Fixed and variable operating costs are estimated based on 40–50 parameters. Fixed operating costs include maintenance material and labor for each process area, plant operating labor, and administrative and support labor. Variable operating costs include consumables (e.g, water treatment chemicals, zinc ferrite sorbent), ash disposal, fuel, and byproduct credit. Total levelized costs are calculated using the financial assumptions and methodology of the Electric Power Research Institute (EPRI, 1986).

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 several types of uncertainty 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 or all 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 (Frey, 1991).

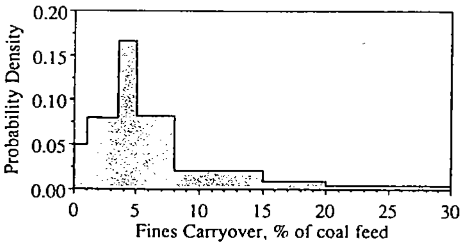

Figure 2. Judgment of expert LG-1 for uncertainty in gasifier fines carryover.

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 some types of uncertainty. For example, the effect of scale-up on process performance may not be fully understood. Thus, analysis of bench-scale test data alone may be an insufficient basis for estimating the total 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 (Morgan and Henrion, 1990).

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 provided judgments regarding key uncertainties. Because the experience 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 each METC expert. 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 some responses (Frey, 1991).

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 based only on their judgments for the parameters in the questionnaire.

A few examples of the expert responses are given here. In the IGCC design assumed here, 30% of the coal feed, on a weight basis, consists of coal fines less than 1/4 in. 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 judgment of expert LG-1 regarding uncertainty in this parameter is shown graphically in Figure 2. The expert indicated that the

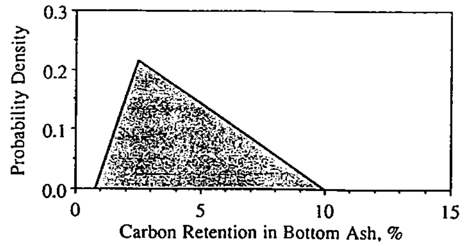

Figure 3. Judgment of expert LG-1 for uncertainty in gasifier bottom ash carbon retention.

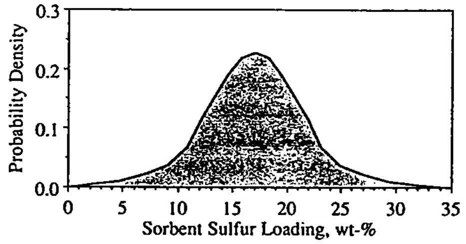

Figure 4. Judgment of expert ZF-1 for uncertainty in sorbent sulfur loading.

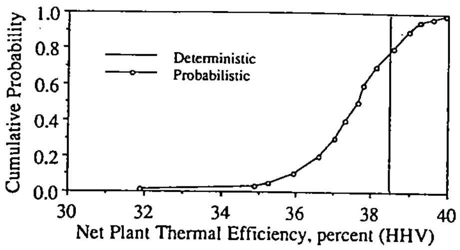

Figure 5. Uncertainty in plant thermal efficiency.

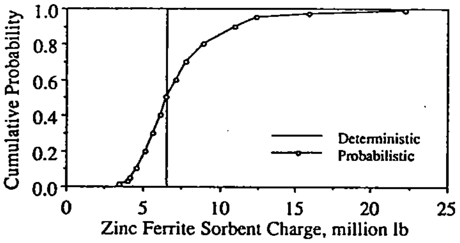

Figure 6. Uncertainty in initial sorbent charge.

uncertainty in coal fines carryover is positively skewed toward high values, with carryover most likely to be 3.5–5% of the coal feed rate.

Expert LG-1 also provided a positively skewed judgment regarding uncertainty for gasifier bottom ash carbon retention, as shown in Figure 3. According to this expert, 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, as shown in Table II. The basis for all uncertainties used in these analyses is given by Frey (1991).

Running the Models. The IGCC models were run on a DEC VAXStation 3200 minicomputer using the public version of ASPEN with the new stochastic modeling capability (Rubin and Diwekar, 1989). A deterministic analysis may take approximately 20–30 min 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 6–12 h 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 Results

The engineering models were exercised in the probabilistic modeling environment to characterize uncertainties in key measures of plant performance, emissions, and cost, based on the uncertainties assigned to model input parameters. Model results are given in Table III for both deterministic point-value and probabilistic simulations. All results reported here are based on a plant size of approximately 650 MW using Illinois No. 6 coal. A few of these results are discussed in more detail.

Uncertainties in Performance and Cost. Estimates of plant thermal efficiency are shown in Figure 5. The deterministic value, based on "best guess" assumptions for all model input parameters, is 38.5%. The probabilistic result is shown as a cumulative distribution function (cdf). The range of values of the uncertain variable are given on the abscissa, and the corresponding fractile from the probability distribution is shown on the ordinate. The cdf is the integral of the probability density function (pdf). It gives the probability of a parameter being at or below a given value. One minus the cumulative probability gives the probability of exceeding the corresponding parameter value.

From the probabilistic simulation, the possible range of values for plant efficiency is from 32 to 40%, with a median (50th percentile) value of 37.7%. The probability distribution is negatively skewed, with a long tail toward lower values. There is only about a 20% chance that efficiency would be higher than the deterministic estimate.

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% 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%, or as high as 10% (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 or 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.

Another key performance parameter is the zinc ferrite sorbent charge, which depends strongly on the sorbent sulfur loading capacity. As previously discussed, expert ZF-1 indicated that the uncertainty is symmetrically distributed, with a mean (and median) at 17 wt %. This median value was used in the deterministic analysis. However, the sorbent charge requirement is a nonlinear function of sorbent sulfur loading (Frey and Rubin, 1990). Therefore, the resulting uncertainty in sorbent charge is

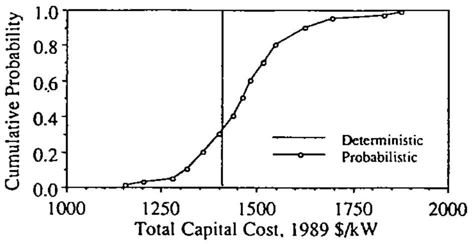

Figure 7. Uncertainty in total capital cost.

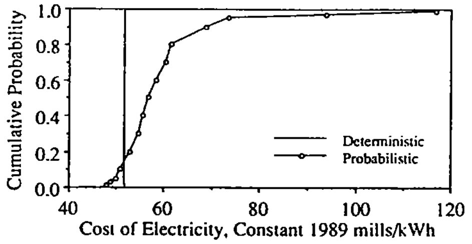

Figure 8. Uncertainty in levelized total cost.

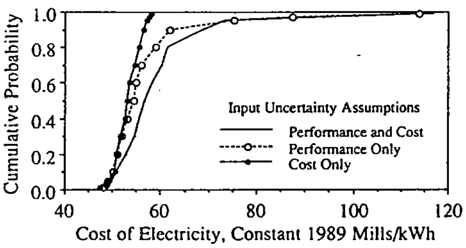

Figure 9. Sources of uncertainty in levelized total cost.

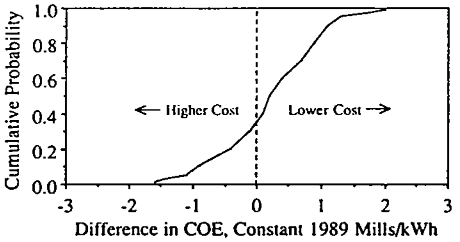

Figure 10. Cost savings from lower pressure drop gas turbine fuel valve.

positively skewed, as shown in Figure 6. Thus, while the calculated median sorbent charge is the same as the deterministic "best guess" value of 6.5 million lb, the mean value is higher, at 7.3 million lb. Furthermore, in the worst case the sorbent charge could be more than 3 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.

Interactions among uncertainties in plant performance and cost parameters lead to uncertainties 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 $1200/kW to over $1800/kW. The mean and median, both approximately $1465/kW, are higher than the deterministic estimate of $1410/kW. There is almost a 70% 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.

The levelized cost of electricity (COE) is the single most comprehensive measure of a plant's economic viability, because it is based on (and sensitive to) all of the performance and cost 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.

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% probability that the COE could be higher than the deterministic estimate, due to the interactions of skewed uncertainties and nonlinearities 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 (Frey, 1991).

Identifying Key Uncertainties. Using statistical techniques, such as multivariate linear regression analysis or variants thereof, 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 IV. These parameters were identified using sample PCCs (Iman et al., 1985). Key parameters 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. Other multivariate regression techniques, such as rank PCCs, sample SRCs, and rank SRCs, also were considered. Although the numerical ranking of key uncertainties differs from one approach to another, the grouping of key uncertainties was similar for all approaches (Frey, 1991).

The interactions among uncertainties also can 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 seen to be the dominant source of the 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. To illustrate an application of probabilistic analysis to process design, an IGCC system with a low pressure drop (20 psi) fuel valve was compared to one with a representative conventional fuel valve (70 psi). Differences in gas turbine cost, if any, associated with the advanced fuel gas valve were 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 of a percentage point, 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.

Table II. Summary of the Base Case Deterministic Values and Uncertainties of the Advanced IGCC System with Hot Gas Cleanup

description and units	det value	distrib and parameters[a]
Gasifier Process Area		
pressure, psia	(calcd)	
temperature, °F	1100	
fines carryover from gasifier, wt % of coal feed	5.0	F; 5%: 0–1 20%: 1–3.5 25%: 3.5–5 25%: 5–8 15%: 8–15 5%: 15–20 5%: 20–30
fines capture in recycle cyclone, %	95	F; 25%: 50–90 25%: 90–95 25%: 95–97 25%: 97–98
fines carbon content, wt %	79	F; 5%: 65–70 20%: 70–75 25%: 75–79 25%: 79–84 25%: 84–87
carbon retention in bottom ash, wt %	2.5	T; 0.75–10 (2.5)
sulfur retention in bottom ash, wt %	3.0	T; 1.5–6 (3)
coal throughput, lb of DAF coal/(h·ft^2)		
250 psia	266	T; 133–333 (266)
300 psia	305	T; 152–381 (305)
350 psia	341	T; 170–426 (341)
ammonia yield, % of coal N	0.9	T; 0.5–1.0 (0.9)
air/coal ratio, lb of air/lb of DAF coal	3.1	T; 2.7–3.4 (3.1)
steam requirement, lb of H_2O/lb of DAF coal		
air/coal = 2.7	0.81	U; 0.54–1.08
air/coal = 3.1	1.55	U; 1.24–1.86
air/coal = 3.4	2.38	U; 2.04–2.72
Zinc Ferrite Desulfurization Process Area		
residual sulfate after oxidative regen, mol % of captured S	7.5	T; 3–11 (7.5)
residual sulfide after reductive regen, mol % of S in sulfate	85	T; 50–90 (85)
sorbent sulfur loading, wt % S in sorbent	17	N; 2.16–31.84
sorbent attrition rate, wt % sorbent loss per cycle	1.0	F; 5%: 0.17–0.34 20%: 0.34–0.5 25%: 0.5–1 25%: 1–1.5 20%: 1.5–5 5%: 5–25
absorber pressure drop, psi/ft bed height	0.4	T; 0.29–0.53 (0.4)
absorption cycle, h	30	
max vessel diam, ft	12.5	
max vessel ht, ft	37.5	
Gas Turbine Process Area		
pressure ratio	13.5	
turbine inlet temperature, °F	2300	
exhaust flow, lb/s	938	
thermal NO_x, fracn of air nitrogen fixated × 10^{-5}	4.25	U; 1.0–7.5
fuel NO_x, % conv of NH_3 to NO_x	90	T; 50–100 (90)
unconverted CO, fraction	0.9885	U; 0.9772–0.9999
Capital Cost Parameters, Fractions		
engineering and home office fee	0.10	T; 0.07–0.13 (0.10)
indirect construction cost factor	0.20	T; 0.15–0.25 (0.20)
project uncertainty	0.175	U; 0.10–0.25
general facilities	0.20	
Direct Cost Contingencies and Uncertainties,[b] % of Estimated Direct Cost		
coal handling	5	U; 0–10
oxidant feed	10	U; 0–20
gasification	20	U; 10–30
cyclones	5	U; 0–10
zinc ferrite	40	U; 0–80
sulfuric acid plant	10	U; 0–20
boiler feed water	0	
gas turbine	25	U; 0–50
HRSG[d]	2.5	U; 0–5
steam turbine	2.5	U; 0–5
general facilities	5	U; 0–10
Maintenance Costs,[c] % of Process Area Total Cost		
coal handling	3	
oxidant feed	2	T; 1–3 (2)
gasification	3	T; 2–12 (3)
cyclones	3	T; 1.5–4.5 (3)
zinc ferrite	3	T; 3–6 (3)
sulfuric acid plant	2	
boiler feed water	1.5	
gas turbine	2	T; 1.5–6 (2)
HRSG[d]	1.5	
steam turbine	1.5	
general facilities	1.5	
Other Fixed Operating Cost Parameters		
labor rate, \$/h	19.70	N; 17.70–21.70
Variable Operating Cost Parameters		
zinc ferrite sorbent, \$/lb	3.00	T; 0.75–5.00 (3.00)
ash disposal, \$/ton	10	T; 10–25 (10)
sulfuric acid byproduct, \$/ton	40	T; 0–60 (40)
byproduct marketing, fraction	0.10	T; 0.05–0.15 (0.10)
Direct Cost Regression Model Error Terms, \$ Million		
boiler feed water	0	N; –0.78 to 0.78
HRSG[d]	0	N; –17.3 to 17.3
steam turbine	0	N; –15.8 to 15.8
boost air compressor	0	N; –0.66 to 0.66
Lurgi coal handling	0	N; –14.4 to 14.4
sulfuric acid plant	0	N; –4.0 to 4.0
Auxiliary Power Regression Model Error Terms		
Lurgi Coal Handling, MW	0	N; –0.35 to 0.35

[a] F = fractile distribution; N = normal distribution; T = triangular distribution; U = uniform distribution. For uniform distributions, the lower and upper bounds are given. For the triangular distribution, the mode is given in parentheses. For the fractile distribution, the lower and upper bounds for each range are given, along with the probability of sampling within that range. For normal and log-normal distribution, the 99.8% probability range is given. [b] For direct costs, the deterministic values represent "contingency factors" as defined by EPRI (1986) and others. For probabilistic studies, uncertainty in capital cost is represented by an uncertainty factor, which is described by a probability distribution. [c] Includes indirect capital costs and contingency costs prorated to each process area. [d] HRSG = heat recovery steam generator.

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 mill/kW-h. However, there still is a 35% 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.

The Value of Additional Research. Additional research may reduce the uncertainties in specific process

Table III. Summary of Results from Deterministic and Probabilistic Simulations of a 650-MW IGCC System with Hot Gas Cleanup[a]

parameter[b]	units[c]	"best guess"[d]	$f_{0.50}$	μ	σ	$f_{0.05}$–$f_{0.95}$
plant performance						
thermal efficiency	%, HHV	38.5	37.7	37.5	1.3	35.3–39.3
coal consumption	lb/kW-h	0.789	0.806	0.811	0.029	0.773–0.861
process water consumption	lb/kW-h	1.604	1.602	1.635	0.261	1.215–2.129
ZF sorbent charge	10^6 lb	6.54	6.51	7.29	2.95	4.15–12.38
sulfuric acid production	lb/kW-h	0.085	0.087	0.087	0.003	0.082–0.093
plant discharges						
SO_2 emissions	lb/MMBtu	0.042	0.040	0.040	0.001	0.038–0.042
NO_x emissions	lb/MMBtu	2.74	2.19	2.19	0.402	1.53–2.84
CO emissions	lb/kW-h	0.003	0.003	0.003	0.003	0.003–0.006
CO_2 emissions	lb/kW-h	1.72	1.73	1.73	0.031	1.68–1.78
solid waste	lb/kW-h	0.083	0.096	0.098	0.015	0.079–0.125
plant costs						
total capital cost	$/kW	1409	1463	1465	127	1281–1696
fixed operating cost	$/kW-yr	44.8	57.2	59.6	10.6	46.4–82.6
variable operating	mills/kW-h	18.2	19.0	21.9	8.6	16.9–36.1
coal		16.2	16.6	16.7	0.6	15.9–17.7
byproduct		(1.5)	(1.4)	(1.3)	0.5	(0.4)–(2.0)
other		3.5	3.7	6.5	8.5	2.2–18.7
cost of electricity[e]	mills/kW-h	51.7	56.7	59.0	9.8	49.9–73.5

[a] The notation in the table heading is defined as follows: f_n = nth fractile ($f_{0.50}$ = median), μ = mean, and σ = standard deviation of the probability distribution. The range enclosed by $f_{0.05}$ to $f_{0.95}$ is the 90% probability range. All costs are January 1989 dollars. [b] Coal consumption is on an as-received basis. Water consumption is for process requirements including makeup for steam cycle blowdown, gasifier steam, and zinc ferrite steam. Solid waste includes gasifier bottom ash and nonrecycled fines from fuel gas cyclones. ZF = zinc ferrite. [c] HHV = higher heating value; MMBtu = million Btu. [d] Based on a deterministic simulation in which median or modal values of uncertain variables are assumed as "best guess" inputs to the model. [e] Levelized, constant dollar basis.

Table IV. 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

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 a 50% reduction of the range of possible values.

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.

To the extent that reduction in uncertainty is a plausible outcome from further research, the comparison of model results with original and reduced uncertainties provides quantitative insight into the potential payoffs from further research.

Effect of Multiple Experts. Typically, deterministic performance and cost estimates are based on one set of model input assumptions. However, process engineers may not always agree on what point-estimate values to use as a "best guess" in a deterministic estimate. Similarly, in the case of probabilistic analysis, there may be more than one expert whose judgment could be obtained to estimate uncertainties for engineering parameters. In our IGCC studies, several experts were asked to provide judgments for the gasification and zinc ferrite process areas. The implications of these alternative judgments for the zinc ferrite process area are briefly discussed.

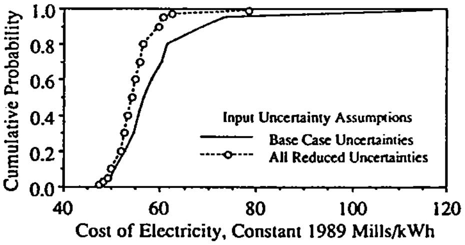

Figure 11. Comparison of total levelized cost results for different uncertainty assumptions.

When more than one set of model input assumptions are available, two approaches are possible. One is to combine the different judgments about either "best guess" or uncertainties prior to running the model. The other is to run separate simulations for each set of input assumption and compare the results. The latter approach is strongly preferred for several reasons. It is not always evident, a priori, whether different judgments lead to significantly different results. Furthermore, if significant differences are obtained, it is then possible to identify the specific judgments that are the source of the differences. Such insight can be used to focus further questioning of experts to try to narrow the differences. However, there may be genuine sources of disagreement that are not easily resolved. In such cases, understanding of the basis for the difference in expert judgments, and the resulting implications for performance and cost results, can help an analyst or decision-maker choose what judgments to weigh more heavily. These types of insights cannot be obtained if expert judgments are combined prior to performing an analysis.

Judgments from three people were obtained, with one expert, ZF-2, providing two sets of responses for the zinc ferrite system. 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. The details of these judgments are given in Frey (1991). Four cases were run in which all IGCC uncertainties were fixed except for differences among the zinc ferrite experts. The deterministic results

Table V. Comparing Multiple Experts: Deterministic "Best Guess" Results

	expert			
parameter, units[a]	ZF-1	ZF-2P	ZF-2R	ZF-3
sorbent charge, 10^6 lb	6.5	9.3	7.7	25.1
total capital cost, $/kW	1410	1440	1410	1570
cost of electricity,[b] mills/kW-h	51.7	55.0	51.4	53.3

[a] All costs are in 1989 dollars. [b] Levelized, constant dollar basis.

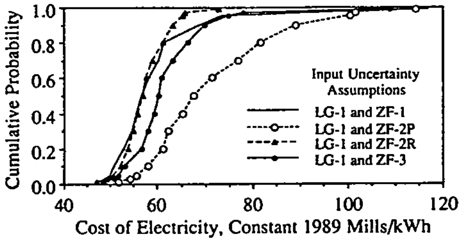

Figure 12. Comparison of total levelized cost results obtained from different experts' judgments.

based on the "best guess" judgments are compared in Table V, and the probabilistic results are compared in Figure 12.

As shown in Table V, the four sets of judgments lead to differences in the estimate for the zinc ferrite sorbent charge, due to different assumptions regarding the "most likely" sorbent sulfur loading capacity. Three of the results are within a relatively narrow range of 6.5–9.3 million lb, while one result is 25.1 million lb. The latter reflects both a lower assumed loading capacity and the nonlinear relationship between sorbent loading and sorbent charge. The total capital cost for all four cases reflects the differences among the experts regarding sorbent sulfur loading. The differences in the results for the cost of electricity are attributable to the experts' judgments regarding both sorbent sulfur loading and the sorbent replacement rate. This is notable in the case of expert ZF-3, whose judgment regarding sorbent sulfur loading led to the highest capital cost, but whose judgment regarding sorbent replacement rate was the lowest of the experts. While the deterministic results for cost of electricity agree within 10%, the underlying assumptions regarding sorbent loading and replacement rate are quite different.

Three sets of probabilistic results are relatively close with respect to central values of the distributions, as shown in Figure 12. Three sets also indicate a probability of very high costs. Only the set based on ZF-2R indicates 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 with respect to the central values for levelized cost. Differences among the experts are attributable to the complex interactions among assumptions that affect the sorbent charge requirement and makeup sorbent. These specific input parameters can targeted for further investigation to reduce disagreements that prove critical to R&D decisions.

Technology Comparisons. The preceding sections have focused on case studies of a single IGCC technology. Often, however, *comparative* results are sought. 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.

The probability distribution for the cost savings of the advanced system over the conventional IGCC system is shown in Figure 13. For example, there is an estimated 73% probability that the new technology will be less expensive than the conventional one by about 5.5 mills/kW-h (or roughly 10%). Conversely, there is a 27% chance the new technology could be more expensive by about 9.5 mills/kW-h (nearly 20%), due primarily to cost uncertainties in the zinc ferrite process area. Overall, the mean savings is 1.5 mills/kW-h.

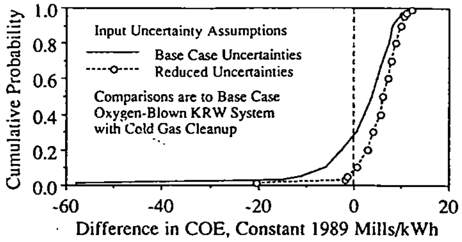

Figure 13. Uncertainty in the total levelized cost savings of advanced technology.

Additional research could change this result, primarily by reducing the risks of the zinc ferrite process. Assuming the reduction in uncertainty for selected parameters in three major process areas as discussed previously, the probability of a cost savings increases to over 90%, and the overall mean savings increases to about 6 mills/kW-h. Similar results are obtained even if uncertainties also are reduced in the conventional technology.

Discussion

Compared to deterministic analysis, the probabilistic modeling approach requires that more effort be devoted to characterizing the range and likelihood of 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 single "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 analyses of new technologies.

As shown in many case studies, the influence of skewed distributions on model results can be important. Skewness in model input parameters tends to shift the central tendency of performance and cost results, and can lead to distributions with long tails representing unfavorable outcomes. These types of interactions cannot be evaluated systematically in deterministic analysis. Thus, while the information requirements for probabilistic analysis may be more demanding, the estimates of performance and cost are likely to be more realistic. Thinking about uncertainties is an important way to gain understanding into the key factors that drive the risk of failure or likelihood of success.

Whether conducting a deterministic or probabilistic analysis, there may be more than one set of judgments or data that can be used as inputs to an analysis. Because model results may depend critically on these assumptions, it is important to consider each set separately. Only those disagreements which really matter need then become the focus for further discussion and evaluation.

Conclusions

An integrated performance and cost model of the Lurgi-based IGCC system has permitted the evaluation of interactions involving the gasification, hot gas cleanup, and power generation process 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 payoffs, *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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Literature Cited

Bajura, R. Gasification and Gas Stream Cleanup Overview. In *Proceedings of the Ninth Annual Gasification and Gas Stream Cleanup Systems Contractor's Review Meeting*; Johnson, R. A., Dorchak, T. P., Eds.; DOE/METC-89/6107 (DE89011706); U.S. Department of Energy Morgantown Energy Technology Center: Morgantown, WV, 1989; Vol. 1, pp 3–11.

Bissett, L. A.; Strickland, L. D. Analysis of a Fixed-Bed Gasifier IGCC Configuration. *Ind. Eng. Chem. Res.* **1991**, *30*, 170–176.

Cool Water. "Cool Water Coal Gasification Program: Fifth Annual Progress Report"; Report No. AP-4832; Electric Power Research Institute: Palo Alto, CA, October 1988.

Corman, J. C. "System Analysis of Simplified IGCC Plants, Topical Report". Report No. DOE/ET/14928-2233; U.S. Department of Energy Morgantown Energy Technology Center: Morgantown, WV, September 1986.

EPRI. "TAG(tm)—Technical Assessment Guide, Volume 1: Electricity Supply—1986"; Report No. P-4463-SR; Electric Power Research Institute: Palo Alto, CA, December 1986.

Frey, H. C. Probabilistic Modeling of Innovative Clean Coal Technologies: Implications for Technology Evaluation and Research Planning. Ph.D. Dissertation, Carnegie Mellon University, Pittsburgh, PA, May 1991.

Frey, H. C.; Rubin, E. S. "Stochastic Modeling of Coal Gasification Combined Cycle Systems: Cost Models of Selected Integrated Gasification Combined Cycle (IGCC) Systems"; Report No. DOE/MC/24248-2901 (DE90015345); U.S. Department of Energy Morgantown Energy Technology Center: Morgantown, WV, June 1990.

Frey, H. C.; Rubin, E. S. "Development and Application of a Probabilistic Evaluation Method for Advanced Process Technologies"; Report No. DOE/MC/24248-3015 (DE91002095); U.S. Department of Energy Morgantown Energy Technology Center: Morgantown, WV, April 1991.

Hager, R. L.; Heaven, D. L. "Evaluation of a Dow-Based Gasification-Combined Cycle Plant Using Bituminous Coal"; Report No. GS-6904; Electric Power Research Institute: Palo Alto, CA, June 1990.

Haldipur, G. B.; Smith, K. J.; Datta, S.; Cherish, P. Fluidized Bed Coal Gasification With Hot Gas Cleanup. In *Proceedings of the Eighth Annual Gasification and Gas Stream Cleanup Systems Contractor's Review Meeting*; Kothari, V. P., Longanbach, J. R., Eds.; DOE/METC-88/6092 (DE88010253); U.S. Department of Energy Morgantown Energy Technology Center: Morgantown, WV, 1988; Vol. 1, pp 32–44.

Hess, R. W.; Myers, C. W. "Assessing Initial Cost Growth and Subsequent Long-Term Cost Improvement in Coal-to-SNG Processes"; Report No. GRI-89/0129; Gas Research Institute: Chicago, IL, June 1989.

Iman, R. L.; Shortencarier, M. J. "A Fortran 77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use With Computer Models"; Report No. SAND83-2365; Sandia National Laboratories: Albuquerque, NM, March 1984.

Iman, R. L.; Shortencarier, M. J.; Johnson, J. D. "A Fortran 77 Program and User's Guide for the Calculation of Partial Correlation and Standardized Regression Coefficients"; Report No. SAND85-0044; Sandia National Laboratories: Albuquerque, NM, June 1985.

Merrow, E. W.; Phillips, K. E.; Myers, C. W. "Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants"; Report No. R-2569-DOE; Rand Corporation: Santa Monica, CA, September 1981.

Morgan, M. G.; Henrion, M. *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*; Cambridge University Press: New York, NY, 1990.

Pietruszkiewicz, J.; Milkavich, R. J.; Booras, G. S.; Thomas, G. O.; Doss, H. "An Evaluation of Integrated Gasification-Combined-Cycle and Pulverized-Coal-Fired Steam Plants"; Report No. AP-5950; Electric Power Research Institute: Palo Alto, CA, September 1988.

Rubin, E. S.; Diwekar, U. M. "Stochastic Modeling of Coal Gasification Combined Cycle Systems"; Report No. DOE/MC/24248-2900 (DE90015570); U.S. Department of Energy Morgantown Energy Technology Center: Morgantown, WV, November 1989.

Stone, K. R. "ASPEN Simulations of Fluidized-Bed and Entrained Flow Integrated Gasification Combined-Cycle Power Plants". Report No. DOE/METC-85/4027 (DE85013620); U.S. Department of Energy Morgantown Energy Technology Center: Morgantown, WV, July 1985.

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