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ENVIRONMENTAL CONTROL IMPLICATIONS OF GENERATING ELECTRIC POWER FROM COAL

COMPARATIVE ASSESSMENTS METHODOLOGY

by

C. David Livengood

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ENVIRONMENTAL CONTROL-
COAL UTILIZATION PROGRAM

ARGONNE NATIONAL LABORATORY

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C. David Livengood

Energy and Environmental Systems Division

June 1977

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Prepared for the
Division of Environmental Control Technology
Assistant Administrator for Environment and Safety
U. S. Energy Research and Development Administration

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FOREWORD

"Environmental Control Implications of Generating Electric Power from Coal" is a continuing Argonne National Laboratory program sponsored by the Division of Environmental Control Technology of the U.S. Energy Research and Development Administration. This is the second in a series of reports issued as part of the program and describes the status of an ongoing effort to develop an appropriate methodology for comparing alternative control technologies. An example comparison is included to illustrate the approach.

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Several Argonne staff members should be recognized for the valuable contributions they made to this report, particularly with regard to the sample technology comparison. Those individuals are:

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*ENVIRONMENTAL CONTROL IMPLICATIONS
OF GENERATING ELECTRIC POWER FROM COAL
COMPARATIVE ASSESSMENTS METHODOLOGY*

ABSTRACT

Environmental control technologies applicable to the coal-to-electricity process are evaluated in an ongoing project at Argonne National Laboratory. Part of the evaluation involves technology comparisons from a total system point of view. This report describes a highly versatile procedure developed for making those comparisons.

The core of the procedure is a simulation mechanism of interconnected modules, each corresponding to a portion of the system stretching from raw coal to power plant emissions. By specifying input and output parameters in a consistent manner, it is possible to combine the modules in a variety of ways to investigate any system of interest. Examples of such parameters are given. New technologies can be added by modifying modules or adding new ones as needed.

Interactions between an analyst and the mechanism are also discussed as they relate to determination of the most significant output factors. Specification of data at different levels of sophistication is described.

As an illustration of the procedure, an example comparison is formulated and carried out in some detail.

1 INTRODUCTION

Coal reserves constitute a valuable energy resource for the United States, and the increased utilization of that resource has become a cornerstone of U.S. energy policy. For that utilization to be socially acceptable, however, close attention must be given to controlling any undesirable environmental consequences. In response to that need, numerous regulations have been promulgated and have stimulated the rapid development of a wide variety of control technologies.

The Energy Research and Development Administration (ERDA) has a responsibility to review the status of these environmental control technologies and to develop independent positions on their technical and economic

feasibilities. To provide assistance in that task, ERDA's Division of Environmental Control Technology has sponsored a technology evaluation program at Argonne National Laboratory (ANL) since March of 1976. The program, entitled "Environmental Control Implications of Generating Electric Power from Coal," is producing a series of reports evaluating control technologies for coal-to-electricity processes from an in-depth engineering and cost point of view.

The first report¹ in the series gave detailed technical descriptions of a number of current and near-term control techniques. Environmental impacts and costs were discussed where the information was available. However, no attempts at comparative evaluations between technologies were made. The purpose of this second report is to discuss the methodology that will be used in the future for such comparisons. Although complete development of the methodology is still well in the future, a basic framework has been adopted and plans have been laid for its implementation on a limited scale for the next major program report in December of 1977. The experience gained in that application will largely define the course of future methodology development.

The need for comparative evaluations is evident when one considers the magnitudes of the investments involved in developing and implementing the technologies in question, combined with the fact that there are generally several competing approaches to solving each environmental problem. It is crucial that the relative advantages, limitations, and development possibilities be clearly delineated for those who must make such investment decisions. It is also important that such evaluations be repeated frequently, since the pace of developments in both the regulatory and technological arenas can quickly render any conclusions obsolete.

The need for a unique methodology may not be so clear, particularly when comparisons of some control technologies (such as flue-gas scrubbers for sulfur oxides) are ubiquitous in the technical literature. Two factors central to the program concept can be cited as demanding a fresh approach. First, the technologies considered span the entire fuel cycle from raw coal processing through power plant waste disposal with many different combinations of the intermediate steps. Also, all environmental impacts and resource commitments are considered. This scope, combined with in-depth engineering analyses, is unique.

Secondly, the program will be considering not only the current approaches to environmental control, but also a number of developing technologies of diverse characteristics. It is essential that a very flexible comparative framework be utilized to accommodate the many possible technology combinations that may need to be evaluated.

The initial phase of the methodology development was carried out under subcontract to Argonne by the Massachusetts Institute of Technology (MIT). A systems analysis approach was used and a highly flexible assessment concept was developed. Initial efforts were also made at defining the crucial technical, economic, and environmental parameters to be considered.

Finally, several possible approaches were described for reducing the data generated to manageable proportions and reaching an ultimate decision regarding the most promising technologies. These points are covered in some detail in Ref. 2, the final report from the MIT subcontract, and will constitute the basis for much of the discussion in this report.

Subsequent to receipt of the MIT report, efforts have centered on adapting the concept to the specific assessment tasks at hand and planning a data management system to cope with the large volume of data that must be accumulated. This process will continue as more information becomes available regarding the various technologies, and as use of the framework indicates necessary refinements.

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2 ASSESSMENT PROCEDURE

The assessment methodology can be best discussed in two stages. First is a simulation mechanism that transforms basic technical information about the technologies into factors quantifying environmental impacts, resource consumption, and economic costs. The second stage is an overall assessment framework, of which the simulation mechanism forms the core. However, it also includes numerous inputs from the user of the methodology, both for specifying the system to be assessed and for assigning priorities to the output factors.

2.1 SIMULATION MECHANISM

The approach chosen for the simulation mechanism involves a highly versatile framework of interconnected modules. Each module represents a significant, and technically separable, portion of the total system stretching from raw coal through emissions from the power plant. A generalized diagram of the framework is shown in Fig. 2.1.

2.1.1 Mechanism Evaluation

While the modular approach is felt to be best for the present application, it is not without drawbacks. In particular, more technical information must be generated for some elements of the system than is the case in the more common total system approach to the problem. Each module must be characterized in enough detail to provide all of the necessary input parameters for the following module. Also, all interrelationships between modules (such as feedback effects) must be fully characterized if the system is to work. These requirements will likely slow the initial pace of the comparative evaluations, but should prove to be beneficial in the longer term as a clearer understanding of the system will necessarily be gained.

The immediate advantages of the modular approach are numerous. It permits evaluations of total coal-to-electricity systems or individual modules using the same data base and calculational procedures. It is obviously flexible, permitting the evaluation of any system of interest through suitable concatenation of modules. In this respect, it provides for a far more comprehensive and timely spectrum of analyses than is the case when all systems to be evaluated must be completely pre-specified.

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Modularity also meshes well with the multidisciplinary approach and extensive use of subcontractors in the ANL program. Firms or individuals with expertise in certain areas can be effectively utilized without requiring that they analyze the total system; a task for which they may be poorly suited. Thus, the total amount of subcontracted work is likely to be reduced with no loss in quality of the comparisons.

Each module is essentially a calculational procedure or model. This disaggregated approach should permit each part of the system to be handled at a level of sophistication commensurate with its importance and the quality of available information. As that importance or information quality changes, the system will be relatively easy to modify. Also, new technologies can be simply added as they develop by inserting new modules or a new option for one of the existing modules.

Finally, this framework provides a logical pathway leading to a computerized system. Computerized models for individual modules can be developed by the project or obtained from outside sources, and tied together as subroutines of an overall evaluation program. Again, updating and additions are facilitated by this structure.

2.1.2 Application of the Mechanism

The initial applications of the simulation mechanism will deal with those environmental control technologies applicable to conventional combustion systems, and will be further restricted to those that can be considered currently available. With those stipulations in mind, the general structure and linkages of Fig. 2.1 have been transformed into a specific group of modules addressing current needs, as shown in Fig. 2.2. The diagram indicates many of the possible relationships between modules, but it is anticipated that others will be revealed and added to the mechanism as the assessments proceed. Solid lines between modules indicate the flow of data and calculated parameters for one typical case while broken lines indicate possible alternatives.

Fig. 2.2. Current Simulation Mechanism

The structure shown can easily accommodate the current and near-term technologies under consideration in the program. However, it is quite possible that attention will eventually be given to advanced concepts that simply cannot be represented within this structure. At that time, the mechanism will have to operate with multiple module configurations, and thereby sacrifice some of the universality that now makes it attractive.

2.1.3 Technical Factors

The technical factors comprise all of the information that is necessary to characterize a given technology. As such, they form part of the input and all of the output for each module. The input factors originate both in *upstream* technologies and, for those factors unique to a given module, in a stored bank of information (data base). Output factors are also of two types. Some of them are passed on to *downstream* modules, forming part of their inputs. Those that are not required elsewhere in the system are simply accumulated and stored until they are needed in the final system performance evaluation. A diagram illustrating these relationships is shown in Fig. 2.3.

Fig. 2.3. Technical Factor Interactions with a Typical Module

The modular nature of the simulation mechanism, with its emphasis on free interchangeability of technologies, demands a highly consistent approach to the specification of technical factors. An initial step is to group the factors into general categories that can be used for all modules. One possible set of categories is shown in Table 2.1.

The exact factors to be included in various categories are still topics of development, and will in any case be subject to modification as the system evolves. In order to illustrate the concept, however, Table 2.2 contains a sample list obtained primarily from Ref. 2. Note that the *Output Characterization* includes factors required by *downstream* modules dealing with the balance of plant, solid waste disposal, and flue gas treatment. For example, the balance of plant module might require a subset of factors consisting of the steam characteristics, capacity factor, availability, and energy consumption.

Table 2.1. Categories of Technical Factors²

Category	Description
Input Characterization	Input information required from the preceding module.
Resource Requirements	Required resources that are not supplied by upstream modules.
Economic Characterization	All dollar measures related to the performance of the technology.
Performance Characterization	All noneconomic performance measures.
Applicability Constraints	Limitations on the utilization of the technology.
Resource Production	By-products of the process that have economic value.
Environmental Consequences	All environmentally related outputs except those included in the output characterization.
Output Characterization	Module output information required by downstream modules.

Table 2.2. Sample Technical Factors for Coal Combustion

Category	Factor
<u>Input Characterization (Coal Characteristics)</u>	Delivered cost (\$/ton) Particle size distribution Grindability index Free swelling index Caking quality Ash fusion temperature (°F) Heating value, dry (Btu/lb) Natural moisture (%) Carbon, dry (%) Volatile matter, dry (%) Ash, dry (%) Oxygen, dry (%) Hydrogen, dry (%) Nitrogen, dry (%) Sulfur, inorganic, dry (%) Sulfur, organic, dry (%) Trace elements: ^a Element name Amount (ppm) Compounds: Compound name Amount (ppm)
<u>Resource Requirements</u>	Manpower: Skill Number Local availability (%) Principal equipment needs Equipment availability constraints Land use (acres) Water use: Process type Consumption (cfs) Chemical use: Chemical Consumption rate (tons/yr) Land use in supply (acres/yr) Water use in supply (acre-ft/yr) Other resource use

Table 2.2 (Contd.)

Category	Factor
<u>Economic Characterization</u>	Capital investment (\$/kW) Labor cost (\$/hr) Maintenance costs (\$/yr) Resource costs: Resource Unit cost (\$) Cost of Utilities (\$/hr)
<u>Performance Characterization</u>	Design capacity (MW) Design availability (%) Forced outage frequency (#/yr) Average forced outage duration (days) Maintenance outage frequency (#/yr) Average maintenance outage duration (days) Energy consumption (kW/MW capacity) Lifetime (yr) Energy conversion efficiency (%)
<u>Applicability Constraints</u>	Probability of technological feasibility (%) Maximum rate of availability (1000 MWe/yr) Site-specific requirements Regional limitations Average licensing time (yr) Potential for advancement of technology
<u>Resource Production</u>	Saleable products: Product Production rate (tons/yr) Market price (\$/ton) Market limits (tons/yr)
<u>Environmental Consequences</u>	Land use (acres) Water use (cfs) Noise level (dba) Occupational health and safety considerations

Table 2.2. (Contd.)

Category	Factor
<u>Output Characterization</u>	Steam characteristics: Pressure (psia) Temperature (°F) Output rate (lb/hr) Capacity factor (%) Availability (%) Energy consumption (kWh/yr) Solid waste: Description Amount (tons/hr) Flue-gas characteristics: Flow rate (acfm) Temperature (°F) Ash loading (lb/acfm) SO _x (lb/acfm) NO _x (lb/acfm) Hydrocarbons (lb/acfm) Trace elements: Element Concentration (ppm) Gas/heat conversion (acfm/Btu) Heat rate (Btu/kWh)

^aThis type of factor may have multiple entries or groups of values.

In spite of the obvious length of the list in Table 2.2, one can easily show that it is only a small portion of the possible set of parameters. For instance, there are literally thousands of different combustion-formed hydrocarbon species. Priorities must therefore be assigned to the factors in order to reduce the data to manageable proportions. The requirements of models or the constraints of data availability will often determine a priori which factors to include. Other cases will require analyses to determine the relative importance of factors in the final cost of power or environmental impacts.

2.1.4 Variable Factors

Technical factors are essentially built into the simulation mechanism, either in the data base or as outputs from the models. On the other hand, variable factors constitute a class of exogenous specifications that are input to the modules by the system user. This relationship is illustrated in Fig. 2.4.

Fig. 2.4 Technical and Variable Factor Interactions with a Typical Module

The most fundamental use of variable factors is the specification of exactly which technologies are to be included in the system under evaluation. Similarly, they would indicate the choice of a particular coal for fuel, the plant location, relevant power system characteristics, and any regulatory constraint not contained in the system. Numerous other factors of a technical nature may also have to be input by the user until such time as fairly sophisticated models are available.

Another important use for these factors is the quantification of variables that are so uncertain that parametric studies are required. Many economic parameters obviously fall into this category, but performance characteristics of developing technologies may also be extremely uncertain. Thus, variable factors could include interest rates on capital, tax rates, the debt/equity ratio, efficiencies, forced outage rates, etc. Several typical factors are given in Table 2.3. as examples.

Table 2.3. Sample Variable Factors^a

Factor	Comment
Coal type	May specify a particular coal of known characteristics (stored in data base) or a generalized coal representative of a region.
Coal transportation mode	If an optimization model is developed for transportation, this may not need to be specified.
Flue-gas scrubber	At the simplest level, this is a yes/no decision. For more sophisticated analyses, the scrubber type would be given.
Plant location	State and county, rural vs. urban, etc.
Cost of land	This will depend upon the location selected.
Date of commercial operation	The year during which full commercial operation begins.
Depreciation method	Straight line, sum-of-the-years digits, etc.
Annual interest rate on debt	This type of factor would likely be varied in parametric studies.

^aThese do not constitute a complete set sufficient for running the simulation mechanism.

2.1.5 Resultant Factors

The output factors from the final module analyzed in the simulation mechanism have special significance since they form the basis for the actual technology comparisons. Therefore, they are termed *resultant factors* to set them apart from all of the other technical and variable factors. These resultant factors may actually originate in several modules, inasmuch as the analysis stream may branch as shown in Fig. 2.2. Also the output technical factors from upstream modules that were not passed on to other modules are retrieved and brought together as additional resultant factors. These relationships are illustrated in Fig. 2.5. A single set of such factors may be sufficient to characterize a given coal-to-electricity process, or several sets may be developed corresponding to parametric variations.

Fig. 2.5. Technical, Variable, and Resultant Factor Interactions with a Typical Module

Care must be taken in formulating the factors and specifying units to ensure that the result is a reasonably sized set of numbers that:

- 1) Contains as much as is possible of the information that might be useful to decision makers having widely varying viewpoints,
- 2) Does not contain any hidden tradeoffs between unlike quantities, and
- 3) Does not contain items of little or no significance that simply tend to obscure the important points.

A number of possible resultant factors are given in Table 2.4.

Table 2.4. Sample Resultant Factors

Category	Factor
<u>Economic Characterization</u>	Total investment (\$) Normalized investment (\$/kW) Fixed operating costs (mills/kWh) Variable operating costs (mills/kWh avg.) Total power cost (mills/kWh)
<u>Performance</u>	Capacity, net (MWe) Capacity, gross (MWe) Capacity factor (%) Availability (%) Energy efficiency (%)
<u>Applicability</u>	Probability of technological feasibility (%) Operating experience (MWe-yr) Commercialization date (year for 2nd full-scale plant) Licensing and construction time (yr)
<u>Resources</u>	Plant area (acres) Waste disposal area (acres) Water consumption (cfs) Chemical consumption: Chemical Amount (tons/yr) By-product production: Product Amount (tons/yr) Manpower required (man-yr/yr)
<u>Environmental Consequences</u>	Airborne emissions: Component Amount (lb/10 ⁶ Btu) Amount (% of applicable standard) Waterborne emissions: Component Amount (lb/10 ⁶ Btu) Amount (% of applicable standard) Solid Wastes: Component Amount (tons/yr) Cooling tower drift salt deposition (tons/yr) Noise at site boundary (dba)

2.2 ASSESSMENT MECHANISM

The assessment mechanism is the procedure by which an analyst interacts with the simulation mechanism described previously. In the interaction, the analyst impresses his preferences and value judgements upon the process so as to obtain results useful in his particular decision-making task.

The term *mechanism* is used since an interactive computerized approach was originally proposed.² This approach has many merits, including speed and widespread availability to potential users. However, it also would require a considerable programming effort that would not contribute materially to the quality of the result. Any such efforts will thus be postponed, and the available computer program development time will be devoted to establishing a data base and calculational models for the various modules.

2.2.1 Assessment Mechanism Structure

The flow of information through the assessment mechanism is best described with the aid of the diagram in Fig. 2.6. The role of the analyst is now explicitly indicated, both in specifying the variable factors and in reducing the numerous resultant factors to those that bear most directly upon the decision to be made. The latter process involves both elimination and ordering of factors, assisted perhaps by graphic display techniques and various strategies to be discussed later (see Sec. 2.2.2). In any case, the resulting factors are referred to as *critical factors* due to their role in the final decision-making process.

Analysis of the critical factors will hopefully provide the information necessary to formulate conclusions regarding the applicability of various fuel/plant/control-technology options. However, in some cases the uncertainties in the data may be such that no clear-cut decision can be made, and areas requiring further investigation will be revealed. In other cases, technologies that are now marginal may have enough advantages delineated to justify research and development efforts designed to improve their commercial competitiveness.

Fig. 2.6 Generalized Assessment Mechanism

2.2.2 Ordering Methods

The input to the ordering procedure can be visualized as a matrix where each of the columns represents a different assessment option and each row contains a different type of resultant factor. In the most general case, each entry could consist of several numbers characterizing the uncertainty in that result. Also, the entries may contain textual material where numeric values are not appropriate or are impossible to derive for lack of data.

A useful ordering procedure must be flexible enough that decision makers with different selection criteria can use it, or that a single analyst can easily represent different points of view. There are numerous strategies available for this task, including threshold criteria, indifference elimination, relative weighting, and utility theory.

The use of utility theory (decision analysis) is in principle well suited to the analysis of quantities having uncertainties. However, it is a relatively new field with many unanswered questions, particularly for multi-attribute decisions.² Thus, no attempt will be made to apply it in the program at this time.

The other strategies mentioned above are more straightforward in application. The use of threshold criteria simply requires the analyst to specify certain values above or below which an alternative should not be considered. These may be government regulations, industry standards, maximum resource availabilities, etc. If there are uncertainty measures associated with the factors, the criteria can be specified in probabilistic terms. For example, given a very detailed probabilistic analysis one might require that all acceptable fuel/plant/control combinations have a 90% probability of meeting the New Source Performance Standards. This technique may well serve to eliminate certain columns from the matrix, but will probably not reduce it sufficiently for a final decision to be made.

Elimination by indifference is a somewhat more subjective approach. Certain resultant factors may be eliminated because the analyst does not consider them to be important relative to the remaining factors. Other factors may be eliminated when the values are essentially the same for all of the assessment options. Provision should be made for reinstating the

values if further analysis reveals that any small differences are indeed significant.

Relative weighting involves application of a multiplicative weight to each resultant factor. Typically, weights between zero and one are used, with zero giving the same result as indifference elimination. Development of the nonzero weights may be highly subjective, but it is this very feature that makes this approach well suited for representing different points of view.

One difficulty arises from the fact that the resultant factors will be in many different units. However, this can be overcome by utilizing the ratio of the value for each factor to the corresponding value for a baseline technology. Once this has been done and the weight applied, a total *figure of merit* for each assessment option can be obtained by summing over all of the factors. Factors that are not numeric in nature must be retained separately, unless they can be quantified through a ranking procedure.

For the initial analyses using this methodology, a combination of threshold criteria and indifference elimination will be used. As more experience is gained and as the analyses become more complex, it is likely that some form of weighting will also be developed and applied.

2.2.3 *Levels of Sophistication*

In the course of the preceding discussion, several references were made to uncertainties in the resultant (or critical) factors. These uncertainties can originate in the models themselves, the original data, or some combination of the two. Those arising in the models are often not quantified, but they can be minimized by careful calibration of the models against real-world systems. This task will be given a high priority, and will be discussed further in subsequent reports as models are gradually incorporated into the simulation mechanism.

Uncertainties in the data can be specified in a number of ways. The particular form depends upon the type of data, the type of uncertainty, and the extent of the available information. Thus, a single type of data specification may not be appropriate for all technical and variable factors. However, the same format must be used for all specifications of any given factor if true interchangeability of technologies is to be realized.

The most complete data specification would include a graphic display of cumulative probability versus value for the factor.² It is anticipated that very little data will be known to this degree of sophistication, and no attempt will be made to use this format.

More useful specifications can be based on the mean value, maximum and minimum values, and the standard deviation. In cases where maxima and minima are not available, they may be replaced by confidence limits such as 5% and 95%. Data for the comparisons will be sought in accordance with this format whenever possible, inasmuch as such uncertainties can usually be carried through to the resultant factors in a fairly straightforward manner.

However, one can readily anticipate that many quantities associated with developing technologies will be known poorly at best, and probability distribution data will be totally out of the question. Other factors, such as the future cost of capital, can only be based on educated guesses. In such cases, parametric studies may prove essential in assessing the effects of variations in crucial factors. For less significant factors, every effort will be made to develop reasonable upper and lower bounds so as to minimize the total number of studies performed.

The question of sophistication also arises in connection with the overall level of the analyses in several areas. These include considerations of isolated plants versus integrated power systems, environmental issues, and economic calculations.

Most of the factors related to control technologies alone can be developed without consideration of location or power system constraints. However, if meaningful comparisons of total coal-to-electricity systems are to be made, such factors must be taken into account. Plant location will affect the choice of coal, the method of coal transportation (and transportation cost), the cost of land, availability of material and labor, the applicable regulations, etc. Power system characteristics can affect the choice of plant size, its required operating characteristics, and the method of financing.

The initial assessment to be performed using the methodology (FY 1977) will concentrate on not more than six different sites located in regions of the country where expansion of coal-fired generating capacity

is anticipated. In this way, it is hoped that a representative picture of the nationwide prospects for control technologies can be developed. Depending upon the significance of the regional issues and the course of regulatory developments, more sites may be added for future comparisons in order to investigate areas where control problems appear to be either particularly difficult or otherwise unique.

The initial comparisons will not consider specific power system constraints. However, in later efforts an attempt may be made to characterize typical systems and to use those characteristics in the analyses if such factors are found to be significant. Some work on the development of such system characteristics has already been sponsored by the Electric Power Research Institute (EPRI) and may prove adaptable to this project.³

The types of environmental information to be generated have already been implied in connection with the technical and resultant factors. In general, impact evaluations will stop at the site boundaries. Exceptions will occur in the case of offsite solid waste disposal and in the treatment of offsite technologies such as coal preparation or conversion plants and transportation facilities. However, no efforts are planned to model effects on air and water quality or the health effects of emissions. In particular, air and water quality issues will be addressed by seeking combinations of technologies that comply with the applicable emission standards.

Once the environmental constraints have been satisfied, economic considerations become crucial in evaluating alternate technologies. The two prime considerations in this area are realism and consistency. For the initial comparisons, parameters typical of current utility practices can be used since all of the technologies have achieved commercial status. Realism in the later comparisons of developing technologies will be more difficult to assure since future conditions must be estimated. All that can be said now is that the system flexibility will readily accommodate updating of parameters to reflect the *best* estimates available at any given time. As mentioned previously in connection with data uncertainties, parametric studies may well be essential in this area.

Consistency is perhaps an even more important factor. The ideal situation would be for all economic calculations to be done by one group of analysts. This will be the case to some extent as the outputs of various

modules are tied together at ANL to provide a total system picture. However, most of the inputs to the modules are being provided by subcontractors. In order to assure consistency in the way they specify costs, development of a list of economic guidelines has been initiated. This list will be refined as the work proceeds, and will be distributed to subcontractors and other personnel as necessary.

In addition to such guidelines, a complete specification of economic assumptions is requested from each technology analyst. In this way, any conflict can be resolved at an early date, or the final numbers can at least be adjusted appropriately.

3 EXAMPLE COMPARISON.

The assessment mechanism has been discussed on a very general basis to this point. In order to clarify the ideas and terminology, and to illustrate the versatility of the approach, an example comparison has been formulated. It must be emphasized that the results cannot be considered definitive in any sense, since the simulation mechanism inputs are based upon preliminary results at best. In many areas where in-depth information has not yet been obtained, estimates by program staff members are used. Finally, the models utilized are extremely simple for most of the modules and may not accurately represent all of the processes.

3.1 TECHNOLOGY DESCRIPTIONS

The comparison involves three different combinations of technologies chosen so as to generally conform to present utility practice. Also, they were chosen so that some of the information being accumulated by the program in the areas of coal preparation and cleaning (CPC) and flue gas desulfurization (FGD) could be used. The primary constraint for each case is that the plant is assumed to be a new installation subject to the federal New Source Performance Standards (NSPS).

The power plant site is assumed to be located near the Illinois River in Marshall County, Illinois, as shown in Fig. 3.1. This area in north-central Illinois is near several demand centers and presently has no generating stations. However, it has been projected to receive 1000 MWe of coal-fired capacity by the year 2000.⁴

Option I is a 500-MWe plant employing a conventional boiler burning Illinois No. 6 coal from Franklin County in southern Illinois. The coal receives treatment only to the extent of crushing and some refuse removal performed at the mine. It is then shipped by unit train to the plant.

A wet limestone FGD system is employed for SO₂ control and for the removal of some of the particulate matter in the flue gas. Mechanical collectors are employed ahead of the scrubber for additional particulates control. The FGD sludge disposal is by simple ponding with no fixation. More details regarding the various components of the system will be supplied in the discussion of individual modules (Sec. 3.2).

Fig. 3.1. Plant Location for Comparison

Option II is similar to I except that western coal from Rosebud County in Montana is used. In this case, the coal preparation consists of crushing and thermal drying at the mine.

A wet scrubber is again employed, although in this case it is used primarily for particulates control since no scrubbing is required to meet the NSPS for SO_2 . A somewhat more realistic approach to particulates collection would be to employ fabric filters (baghouse), and this option will be investigated in future comparisons.

Option III is designed to investigate the feasibility of combining the previous two cases to achieve an economic advantage. A blended coal is utilized, consisting of 60% Montana and 40% Illinois coals. Only part of the flue-gas stream is scrubbed, with the remainder being bypassed. The two streams are recombined, thereby drastically reducing the need for reheating of the scrubbed gases.

In each option, the plant is assumed to function as a base-load facility with an initial capacity factor of 80%. Startup is projected for 1979. Escalation of costs is handled primarily through projection of the cost indices for materials and labor appearing in the publication Chemical Engineering.

3.2 SIMULATION MECHANISM

The following sections present the factors associated with each of the modules in the simulation mechanism. The number of factors, as well as the degree of technical and economic detail, has purposely been kept to a minimum so as not to obscure the interplay of modules.

3.2.1 Coal Characteristics

Coal characteristics can vary dramatically from sample to sample, even within the same seam in a single mine. It is thus nearly impossible to speak meaningfully of a typical coal. For this comparison, characteristics were chosen that appeared to be representative of coals obtained from a certain mining region, and that were consistent with samples used in a study on coal preparation and cleaning performed for this program.⁵ Tables 3.1 and 3.2 give the technical factors for each coal before any preparation is performed.

Table 3.1. Variable and Technical Factors for Illinois No. 6 Coal⁶

Factor Type	Factor	Value
<u>Variable</u>		
	State	Illinois
	County	Franklin
	Coal bed	No. 6
	Coal identifier	IL6
	Mine type	Deep
	Year	1979
<u>Technical</u>		
Output	Coal identifier	IL6
	Moisture (%)	4.10 ^a
	Volatile matter (%)	34.1
	Fixed carbon (%)	52.0
	Ash (%)	7.20
	Sulfur, total (%)	2.58
	Hydrogen (%)	4.80
	Carbon (%)	72.2
	Nitrogen (%)	1.50
	Oxygen (%)	7.52
	Chlorine (%)	0.10
	Heat content (Btu/lb)	12790
	Ash softening temp. (°F)	2350
	Free swelling index	1.0-5.0
	Hardgrove grindability index	52-62
	Price (\$/ton)	20

^aAll values are weight percentages for as-received conditions unless otherwise noted.

Table 3.2. Variable and Technical Factors for Montana Rosebud Coal⁶

Factor Type	Factor	Value
<u>Variable</u>		
	State	Montana
	County	Rosebud
	Coal bed	Rosebud
	Coal identifier	MTRB
	Mine type	Strip
	Year	1979
<u>Technical</u>		
Output	Coal identifier	MTRB
	Moisture (%)	24.1 ^a
	Volatile matter	29.1
	Fixed carbon (%)	39.5
	Ash (%)	6.76
	Sulfur, total(%)	0.55
	Hydrogen (%)	3.51
	Carbon (%)	52.8
	Nitrogen (%)	0.79
	Oxygen (%)	11.4
	Chlorine (%)	0.09
	Heat content (Btu/lb)	9054
	Ash softening temp. (°F)	2240
	Free swelling index	NA ^b
	Hardgrove grindability index	44-51
	Price (\$/ton)	6

^aAll values are weight percentages for as-received conditions unless otherwise noted.

^bNot available.

There are many other coal parameters that could be included in the tables, particularly with regard to trace elements and resource characterization. However, the factors presented are representative of the information available on many coals and are sufficient to satisfy the needs of downstream models in the mechanism.

3.2.2 Coal Preparation and Cleaning

The coal treatment chosen for this example (designated as Level 1 preparation) is quite simple and involves no sulfur removal. It is assumed to be performed at or near the mine in each case. Screening and crushing

are the primary operations involved, with an added drying step for the Montana coal. A block diagram of the processes as applied to Option III is given in Fig. 3.2. A more extensive discussion of the technologies involved may be found in Ref. 5.

The technical and variable factors for coal preparation are given in Table 3.3 and Table 3.4 for Illinois and Montana coal, respectively. Note that most economic parameters have been omitted inasmuch as it is assumed all costs are reflected in an incremental charge added to the price of the coal.

Some of the environmental impacts of coal preparation are included, although where possible they are normalized to 10^6 tons of product. This is required since the plant designs utilized⁵ are sized to produce 3.25×10^6 tons of product per year (dry basis) while the power plants being compared require only about 1×10^6 tons per year. The exact amount is not specified at this point in the analysis and thus constitutes a feedback loop that must be fulfilled later. However, it is assumed that the preparation plants have enough potential customers that they can be operated at full capacity and thus processing costs should not depend on the volume required by the power plant.

3.2.3 Coal Transportation

All coal transportation is assumed to be via unit train from the preparation facilities to the plant site. Some environmental residuals are to be expected in the course of train (locomotive) operation. However, a preliminary analysis has indicated that they are small compared to those arising elsewhere in the system and they are thus omitted in this comparison.

The model used to calculate transportation costs was developed at ANL.⁷ Although allowance is made in the model for the effect of annual volume shipped, the effect is insignificant for any but very small volumes and has therefore been disregarded. If this were not the case, another feedback loop would be added requiring determination of the plant characteristics before calculating final shipping cost.

Tables 3.5 and 3.6 give the transportation factors for each of the coals in this comparison.

Fig. 3.2 Block Diagram of Coal Preparation Processes

Table 3.3. Variable and Technical Factors for Preparation of Illinois No. 6 Coal

Factor Type	Factor	Value
<u>Variable</u>		
	Coal identifier	IL6
	Preparation and cleaning level ⁵	1
	Preparation plant location (state)	IL
	Process options	-
	Year	1979
<u>Technical</u>		
Input	(See Output in Table 3.1)	
Resources	Water consumption (gal/10 ⁶ tons product)	0
	Fuel consumption (Btu/ton product)	0
	Plant land use (acres)	10
	Waste disposal land commitment (acres/10 ⁶ tons product)	0.6
	Electricity consumption (kWh/10 ⁶ tons product)	0.43x10 ⁶
Economics	Processing cost (\$/ton product)	0.50
	Material loss cost (\$/ton product)	0
Performance	Material loss (tons/ton input)	0
Environmental	Waste disposal burden (tons/10 ⁶ tons product) ^a	2.9x10 ⁴
Output	Coal identifier	IL6
	Moisture (%)	4.10
	Volatile matter (%)	34.1
	Fixed carbon (%)	52.0
	Ash (%)	7.20
	Sulfur, total (%)	2.58
	Hydrogen (%)	4.80
	Carbon (%)	72.2
	Nitrogen (%)	1.50
	Oxygen (%)	7.52
	Chlorine (%)	0.10
	Heat content (Btu/lb)	12790
	Ash softening temp. (°F)	2350
	Free swelling index	1.0-5.0
	Hardgrove grindability index	52-62
	Total coal cost (\$/ton)	20.50

^a Mine refuse.

Table 3.4. Variable and Technical Factors for Preparation of Montana Rosebud Coal

Factor Type	Factor	Value
<u>Variable</u>		
	Coal identifier	MTRB
	Preparation and cleaning level ⁵	1
	Preparation plant location (state)	MT
	Process options	Drying
	Year	1979
<u>Technical</u>		
Input	(See Output in Table 3.2)	
Resources	Water consumption (gal/10 ⁶ tons product)	0
	Fuel consumption (Btu/ton product)	4.25x10 ⁵
	Plant land use (acres)	10
	Waste disposal land commitment (acres/10 ⁶ tons product)	0
	Electricity consumption (kWh/10 ⁶ tons product)	0.76x10 ⁶
Economics	Processing cost (\$/ton product)	0.83
	Material loss cost (\$/ton product)	1.00
Performance	Material loss (tons/ton input) ^a	0.14
Environmental	Waste disposal burden (tons/10 ⁶ tons product)	0
Output	Coal identifier	MTRB
	Moisture (%)	13.6
	Volatile matter (%)	33.1
	Fixed carbon (%)	45.0
	Ash (%)	7.70
	Sulfur, total (%)	0.62
	Hydrogen (%)	4.00
	Carbon (%)	60.1
	Nitrogen (%)	0.90
	Oxygen (%)	13.0
	Chlorine (%)	0.10
	Heat Content (Btu/lb)	10307
	Ash softening temp. (°F)	2240
	Free swelling index	NA
	Hardgrove grindability index	44-51
	Total coal cost (\$/ton)	7.83

^aLargely moisture. This must be considered as material lost since the coal cost is calculated on a per ton basis as it is delivered to the processing plant.

Table 3.5. Variable and Technical Factors for Transportation of Illinois No. 6 Coal

Factor Type	Factor	Value
<u>Variable</u>		
	Coal identifier	IL6
	Rail distance (miles) ⁸	256
	Year	1979
<u>Technical</u>		
Input	(See Output in Table 3.3)	
Resources	Fuel consumption ^a (Btu/ton coal) ⁹	1.00x10 ⁵
Economics	Transportation cost (\$/ton)	3.63
Output	Coal identifier	IL6
	Moisture (%)	4.10
	Volatile matter (%)	34.1
	Fixed carbon (%)	52.0
	Ash (%)	7.20
	Sulfur (%)	2.58
	Hydrogen (%)	4.80
	Carbon (%)	72.2
	Nitrogen (%)	1.50
	Oxygen (%)	7.52
	Chlorine (%)	0.10
	Heat content (Btu/lb)	12790
	Ash softening temp. (°F)	2350
	Free swelling index	1.0-5.0
	Hardgrove grindability index	52-62
	Total delivered coal cost (\$/ton)	24.13

^aRound trip consumption of diesel fuel.

Table 3.6. Variable and Technical Factors for Transportation of Montana Rosebud Coal

Factor Type	Factor	Value
<u>Variable</u>		
	Coal identifier	MTRB
	Rail distance (miles) ⁸	1392
	Year	1979
<u>Technical</u>		
Input	(See Output in Table 3.4)	
Resources	Fuel consumption ^a (Btu/ton coal) ⁹	5.46x10 ⁵
Economics	Transportation cost (\$/ton)	12.78
Output	Coal identifier	MTRB
	Moisture (%)	13.6
	Volatile matter (%)	33.1
	Fixed carbon (%)	45.3
	Ash (%)	7.70
	Sulfur (%)	0.62
	Hydrogen (%)	4.00
	Carbon (%)	60.1
	Nitrogen (%)	0.90
	Oxygen (%)	13.0
	Chlorine (%)	0.10
	Heat content (Btu/lb)	10307
	Ash softening temp. (°F)	2240
	Free swelling index	NA
	Hardgrove grindability index	44-51
	Total coal cost (\$/ton)	20.61

^aRound trip consumption of diesel fuel.

3.2.4 *Coal Storage and Handling*

Coal storage and handling was indicated as a separate module in Fig. 2.2. However, it constitutes a very small part of the total plant investment and has not been the subject of any detailed studies as part of this project. Most of the following information is based upon information obtained from Ref. 10.

Coal is received in uncovered rail cars equipped for rotary dumping. After dumping into underground hoppers, it is transported via conveyor to the coal storage area. In all cases a long-term reserve storage sufficient for about 60 days is maintained, with a live pile sufficient for about two days of operation used under normal conditions.

In Option I and Option II the coal reclaim system transports coal from the live pile via conveyor belt to a surge bin in the powerhouse. From that point, the equipment is considered to be part of the combustion module.

Option III (blending) is similar except that two coal storage areas are required, one for each coal type. The reclaim system brings the coals together in the proper proportions before conveying the mixture to the surge bin. Tables 3.7, 3.8 and 3.9 give the relevant factors for each option.

3.2.5 *Combustion*

The major equipment items in this module consist of the boiler and coal pulverizers. It is assumed that these items are similar for all three options except for differences in size brought about by the different heat contents of the coals and their different grindability and slagging characteristics. Drying of the western coal during preparation removes the need for additional drying at the pulverizers.

Boiler design is of the balanced draft, direct fired, pulverized coal type. Six pulverizing mills are utilized, each capable of supplying about 50 tons of coal per hour at maximum capacity. Regenerative air heaters are used to lower the exit gas temperature. Tables 3.10, 3.11 and 3.12 give the factors for each option. The values are based upon information in Ref. 10 and the computer program described in Ref. 11.

Table 3.7. Option I Coal Storage and Handling Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Coal 1 identifier	IL6
	Coal 2 identifier	-
	Number of coal storage areas	1
	Blending (Yes/No)	No
	Blending proportions (Coal 1/Coal 2)	-
	Approximate yearly volume (10^6 tons)	1.2
	Year	1979
<u>Technical</u>		
Input	(See Output in Table 3.5)	
Resources	Electricity consumption (MW)	1.0
	Land area (acres)	11.0
Economics	Capital cost (10^6 \$)	3.9
Output	(Same as Input)	

Table 3.8. Option II Coal Storage and Handling Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Coal 1 identifier	MTRB
	Coal 2 identifier	-
	Number of coal storage areas	1
	Blending (Yes/No)	No
	Blending proportions (Coal 1/Coal 2)	-
	Approximate yearly volume (10^6 tons)	1.6
	Year	1979
<u>Technical</u>		
Input	(See Output in Table 3.6)	
Resources	Electricity consumption (MW)	1.3
	Land area (acres)	15.0
Economics	Capital cost (10^6 \$)	4.9
Output	(Same as Input)	

Table 3.9. Option III Coal Storage and Handling Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Coal 1 identifier	IL6
	Coal 2 identifier	MTRB
	Number of coal storage areas	2
	Blending (Yes/No)	Yes
	Blending proportions (Coal 1/Coal 2)	4/6
	Approximate yearly volume (10^6 tons)	1.4
	Year	1979
<u>Technical</u>		
Input	(Outputs from Tables 3.5 and 3.6)	
Resources	Electricity consumption (MW)	1.4
	Land area (acres)	13.0
Economics	Capital cost (10^6 \$)	6.6
Output	Coal identifier	IL6/MTRB
	Moisture (%)	9.80
	Volatile matter (%)	33.5
	Fixed carbon (%)	48.0
	Ash (%)	7.50
	Sulfur (%)	1.40
	Hydrogen (%)	4.32
	Carbon (%)	64.9
	Nitrogen (%)	1.14
	Oxygen (%)	10.8
	Chlorine (%)	0.10
	Heat content (Btu/lb)	11300
	Ash softening temp. ($^{\circ}$ F)	2240-2350
	Free swelling index	NA
	Hardgrove grindability index	44-62
	Total coal cost (\$/ton)	22.0

Table 3.10. Option I Combustion Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Plant size, gross (MWe)	500
	Boiler type	Pulverized coal
	Heat rate (Btu/kWh)	9000
	Excess air (%)	20
	Sulfur overhead (%)	95
	Ash overhead (%)	80
	Year	1979
<u>Technical</u>		
Input	(See Output in Table 3.7)	
Resources	Coal firing rate (tons/hr)	175.9
	Electricity consumption (MW)	20
	Land area (acres)	0.8
Economics	Capital cost (10^6 \$)	60
Output	Steam temp. ($^{\circ}$ F)	1000
	Steam pressure (psig)	2650
	Bottom ash (lb/hr)	0.51×10^4
	Fly ash (lb/hr)	0.20×10^5
	Hot gas composition (lb/hr):	
	CO ₂	0.93×10^6
	HCl	0.36×10^3
	SO ₂	0.17×10^5
	O ₂	0.16×10^6
	N ₂	0.32×10^7
	H ₂ O	0.22×10^6
	Hot gas flow rate (ACFM)	0.14×10^7
	Hot gas temperature ($^{\circ}$ F)	300

Table 3.11. Option II Combustion Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Plant size, gross (MW _e)	500
	Boiler type	Pulverized coal
	Heat rate (Btu/kWh)	9400
	Excess air (%)	20
	Sulfur overhead (%)	95
	Ash overhead (%)	80
	Year	1979
<u>Technical</u>		
Input	(See Output in Table 3.8)	
Resources	Coal firing rate (tons/hr)	228
	Electricity consumption (MW)	23
	Land area (acres)	0.8
Economics	Capital cost (10 ⁶ \$)	64
Output	Steam temp. (°F)	1000
	Steam pressure (psig)	2650
	Bottom ash (lb/hr)	0.70x10 ⁴
	Fly ash (lb/hr)	0.28x10 ⁵
	Hot gas composition (lb/hr):	
	CO ₂	0.10x10 ⁷
	HCl	0.47x10 ³
	SO ₂	0.54x10 ⁴
	O ₂	0.16x10 ⁶
	N ₂	0.33x10 ⁷
	H ₂ O	0.28x10 ⁶
	Hot gas flow rate (ACFM)	0.15x10 ⁷
	Hot gas temperature (°F)	300

Table 3.12. Option III Combustion Factors

Factory Type	Factor	Value
<u>Variable</u>		
	Plant size, gross (MWe)	500
	Boiler type	Pulverized coal
	Heat rate (Btu/kWh)	9160
	Excess air (%)	20
	Sulfur overhead (%)	95
	Ash overhead (%)	80
	Year	1979
<u>Technical</u>		
Input	(See Output in Table 3.9)	
Resources	Coal firing rate (tons/hr)	204
	Power consumption (MW)	21
	Land area (acres)	0.8
Economics	Capital cost (10^6 \$)	63
Output	Steam temp. ($^{\circ}$ F)	1000
	Steam pressure (psig)	2650
	Bottom ash (lb/hr)	0.62×10^4
	Fly ash (lb/hr)	0.25×10^5
	Hot gas composition (lb/hr):	
	CO ₂	0.97×10^6
	HCl	0.42×10^3
	SO ₂	0.10×10^5
	O ₂	0.16×10^6
	N ₂	0.32×10^7
	H ₂ O	0.25×10^6
	Hot gas flow rate (ACFM)	0.14×10^7
	Hot gas temperature ($^{\circ}$ F)	300

3.2.6 *Flue Gas Treatment*

All flue-gas treatment is combined into one module for this comparison. That module consists primarily of a wet limestone scrubber utilized for both sulfur and particulates removal. However, mechanical collectors are also incorporated into the FGD system and these remove about one third of the particulates from the flue gas before it reaches the scrubber.

In Option II (Montana coal), the scrubber functions mainly as a particulates removal device, as described in Sec. 3.1. Option III (blended coal) applies FGD to slightly more than half of the flue gas, bypassing the remainder. After scrubbing, the two streams are recombined, thus reducing the gas reheat requirement.

Most of the technical factors are based upon calculations made using the computer program described in Ref. 11. Since this module is the termination of one branch of the mechanism structure, some of the factors are specified as "resultant factors." Other factors are still designated as "output" since they are required by the sorbent storage and handling module and the solid waste disposal module. The significant input and output parameters are given Tables 3.13, 3.14 and 3.15.

3.2.7 *Sorbent Storage and Handling*

This module uses the flue-gas scrubber sorbent requirements together with several user-supplied parameters to develop characteristics for the storage and handling equipment. Most of the values utilized in this example were developed by the same program used for the FGD system,¹¹ but they have been broken out separately to conform with the structure shown previously.

The system includes the equipment necessary for receiving limestone by rail, a storage stockpile, conveyors, and wet ball mills for crushing the stone. Slurry from the mills is pumped to the scrubbing area for distribution. Water is supplied from the waste disposal pond supernate.

Relatively few factors are used for this module. Therefore, all of the options have been treated in Table 3.16 in the interest of brevity.

Table 3.13. Option I Flue Gas Treatment Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Scrubber type	Wet Limestone TCA ^a
	Portion of gas scrubbed (%)	100
	Mechanical collector efficiency (%)	33
	Number of scrubber trains	4
	Number of redundant trains	0
	Gas velocity (ft/sec)	10
	Stoichiometry (mole CaCO ₃ /mole SO ₂)	1.54
	SO ₂ concentration in outlet gas (ppm)	518
	Outlet flue gas temperature (°F)	175
	Year	1979
<u>Technical</u>		
Input	(Uses part of Output in Table 3.10)	
Resources	Makeup water (gpm)	560
	Electricity consumption (MW)	3
	Steam use (10 ³ lb/hr)	86.6
	Land area (acres)	0.6
Economics	Capital cost (10 ⁶ \$)	14.0
Performance	SO ₂ removal efficiency (%)	68.7
	Particulates removal efficiency (%)	99.5
Output	Limestone consumption (lb/hr)	2.94x10 ⁴
	Sludge discharge flow rate (gpm)	189
	Sludge mass flow (lb/hr)	1.25x10 ⁵
	Solids in sludge (%)	40.0
Resultant	Stack-gas composition (lb/hr):	
	CO ₂	0.959x10 ⁶
	SO ₂	0.539x10 ⁴
	O ₂	0.158x10 ⁶
	N ₂	0.316x10 ⁷
	H ₂ O	0.423x10 ⁶
	Fly ash	0.68x10 ²

^aTurbulent contact absorber.

Table 3.14. Option II Flue Gas Treatment Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Scrubber type	Wet Limestone TCA
	Portion of gas scrubbed (%)	100
	Mechanical collector efficiency (%)	33
	Number of scrubber trains	4
	Number of redundant trains	0
	Gas velocity (ft/sec)	10
	Stoichiometry (mole CaCO_3 /mole SO_2)	3.0
	SO_2 concentration in outlet gas (ppm)	400
	Outlet flue gas temperature ($^{\circ}\text{F}$)	175
	Year	1979
<u>Technical</u>		
Input	(Uses part of Output in Table 3.11)	
Resources	Makeup water (gpm)	485
	Electricity consumption (MW)	2
	Steam use (10^3 lb/hr)	85.1
	Land area (acres)	0.4
Economics	Capital cost (10^6 \$)	12.7
Performance	SO_2 removal efficiency (%)	18.2
	Particulates removal efficiency (%)	99.5
Output	Limestone consumption (lb/hr)	4.71×10^3
	Sludge discharge flow rate (gpm)	88
	Sludge mass flow (lb/hr)	5.84×10^4
	Solids in sludge (%)	40.0
Resultant	Stack-gas composition (lb/hr):	
	CO_2	0.100×10^7
	SO_2	0.439×10^4
	O_2	0.164×10^6
	N_2	0.326×10^7
	H_2O	0.488×10^6
	Fly ash	0.94×10^2

Table 3.15. Option III Flue Gas Treatment Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Scrubber type	Wet Limestone TCA
	Portion of gas scrubbed (%)	56
	Mechanical collector efficiency (%)	33
	Number of scrubber trains	2
	Number of redundant trains	0
	Gas velocity (ft/sec)	10
	Stoichiometry (mole CaCO_3 /mole SO_2)	1.54
	SO_2 concentration in outlet gas (ppm)	102
	Outlet flue gas temperature ($^{\circ}\text{F}$)	125
	Year	1979
<u>Technical</u>		
Input	(Uses part of Output in Table 3.12)	
Resources	Makeup water (gpm)	304
	Electricity consumption (MW)	2.0
	Steam use (10^3 lb/hr)	1.24
	Land area (acres)	0.2
Economics	Capital cost (10^6 \$)	7.39
Output	Limestone consumption (lb/hr)	1.30×10^4
	Sludge discharge flow rate (gpm)	95
	Sludge mass flow (lb/hr)	6.31×10^4
	Solids in sludge (%)	40.0
Resultant	Stack-gas composition (lb/hr):	
	CO_2	0.969×10^6
	SO_2	0.527×10^4
	O_2	0.160×10^6
	N_2	0.319×10^7
	H_2O	0.364×10^6
	Fly ash	1.1×10^4

Table 3.16. Sorbent Storage and Handling Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Sorbent type	Limestone
	Shipping mode	Rail
	Unit cost (\$/ton)	6.50
	Year	1979
<u>Technical</u>		
Input	(Output from Table 3.13, 3.14, or 3.15 as appropriate)	
Resources	Electricity consumption (MW):	
	Option I	0.59
	Option II	0.10
	Option III	0.26
	Sorbent consumption (lb/hr):	
	Option I	2.94×10^4
	Option II	4.71×10^3
	Option III	1.30×10^4
	Land area (acres):	
	Option I	1.8
	Option II	1.8
	Option III	1.8
Economics	Capital cost (10^6 \$):	
	Option I	1.823
	Option II	1.670
	Option III	1.662
Resultant	Sorbent cost (\$/hr):	
	Option I	95.55
	Option II	15.31
	Option III	42.25

3.2.8 Solid Waste Disposal

This module is similar to the one discussed in Sec. 3.2.7 in that most of the values presented were developed by the computer program used for the FGD system.¹¹ The disposal model utilizes onsite ponding with no sludge fixation. Supernate from the settling pond is recycled to maintain a closed system.

The factors for all three options are presented in the following table. No resultant factors are shown because each of the parameters has yet to be combined with corresponding values from other modules in order to form the final results.

Table 3.17. Solid Waste Disposal Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Pond depth (ft)	25
	Distance to pond (ft)	2640
	Liner material	Clay
	Liner thickness (in)	12.0
	Solids settling rate (ft/hr)	0.20
	Year	1979
<u>Technical</u>		
Input	(Output from Table 3.13, 3.14, or 3.15 as appropriate)	
Resources	Electricity consumption (MW)	
	Option I	0.45
	Option II	0.21
	Option III	0.23
	Land area (acres)	
	Option I	256.2
	Option II	142.2
	Option III	150.8
Economics	Capital cost (10 ⁶ \$) ^a	
	Option I	5.710
	Option II	3.428
	Option III	3.665

^aExcluding cost of land.

3.2.9 Balance of Plant

The balance of plant (BOP) includes all equipment and facilities not included in the other modules. In particular, it includes such major items as the turbine-generator, condenser, feedwater system, and condenser cooling system. There are also numerous structures and auxiliary systems. However, none of these bear directly upon the environmental control systems or techniques that are the objects of this comparison, and will not be treated in any detail here since the complexities are clearly beyond the scope of this example.

In general, the BOP is assumed to conform to current design practices and is essentially the same for all three options. Condenser cooling is by mechanical draft towers with makeup water pumped from the nearby Illinois River. Blowdown water is returned to the river. The total site area is taken as 600 acres, although only part of that is actually required for the plant. The remainder is retained in its natural state and reserved for future expansion. The following table gives the factors considered.

Table 3.18. Balance of Plant Factors

Factor Type	Factor	Value
<u>Variable</u>		
	Location (state)	IL
	Cooling type	Mechanical-Draft Towers
	Gross output (MW _e)	500
<u>Technical</u>		
Input	(Output from Table 3.10, 3.11, or 3.12 as appropriate)	
Resources	Electricity consumption (MW) All options	17
	Land area (acres) All options	30
	Water consumption, evaporation (gpm) All options	3600
<u>Economics</u>		
	Option I	162
	Option II	168
	Option III	165

3.3 CONCLUSIONS

Up to this point a great deal of data has been generated, even in this extremely simplified example. However, it is doubtful that any clarification of the fuel choice question has yet resulted. In order to accomplish that end, a listing of all resultant factors must now be compiled, as shown in Table 3.19. Some of the factors are simply transferred from previous tables. Others are generated by suitably combining factors that were placed aside and saved in the course of the analysis. For example, onsite land acreage used is compiled from the resource factors of six modules.

Capital costs are somewhat more involved. All of the figures presented previously are first compiled. Then, suitable amounts for such additional costs as engineering and contractor fees, contingency allowance, interest during construction, etc. are added to obtain the total capital investment. For this example, the accounting approach discussed in Ref. 11 has been utilized and applied consistently to all three cases. A plant capacity factor of 0.8 is assumed for the power cost calculations, as well as an 18% annual charge rate applied to the total capital investment.

The results shown are obviously similar for all three options and can hardly be considered significant in view of the preliminary nature of much of the input data. However, in the interest of following the assessment mechanism through to completion, critical factors must now be developed by applying some form of elimination or other techniques as described previously.

Assume that the analyst is indifferent to:

1. offsite resource requirements,
2. limestone, fuel, and water use,
3. solid waste volumes,
4. all airborne effluents except SO₂ and ash, and
5. all costs except total capital and the total cost of electricity.

Furthermore, note that the net outputs do not vary significantly, so that they may also be eliminated. A table of critical factors (Table 3.20) can now be constructed to illustrate any crucial differences. Electricity and steam use have been combined in the table and the units for airborne effluents are changed to conform with the usual regulatory format.

Table 3.19 Resultant Factors

Factors ^{a,b}	Option I Illinois Coal	Option II Montana Coal	Option III Blended Coal
Resource requirements:			
Offsite facility land (acres)	10	10	20
Offsite waste disposal land (acres/yr)	0.74	0	0.34
Offsite water use (gpm)	0	0	0
Offsite fuel use (Btu/yr)	1.23×10^{11}	1.55×10^{12}	8.92×10^{11}
Offsite electricity use (kWh/yr)	5.29×10^5	1.22×10^6	8.99×10^5
Facility land (acres)	44.2	48.0	45.8
Waste disposal land (acres)	256	142	151
Water use (gpm)	4.16×10^3	4.08×10^3	3.90×10^3
Fuel use (Btu/yr)	3.15×10^{13}	3.29×10^{13}	3.23×10^{13}
Electricity use (kWh/yr)	2.94×10^8	3.05×10^8	2.93×10^8
Steam use (kWh/yr equivalent)	6.06×10^7	5.96×10^7	8.68×10^5
Limestone use (tons/yr)	1.03×10^5	1.65×10^4	4.55×10^4
Economic characterization:			
Coal cost (10^6 \$/yr)	29.7	33.0	31.5
Direct capital cost (10^6 \$)	247	255	247
Indirect capital cost (10^6 \$)	165	170	165
Land cost (10^6 \$)	1.20	0.76	0.79
Total capital cost (10^6 \$)	413	426	413
Electricity cost (mills/kWh):			
Capital	23.2	24.0	23.2
Operation & Maintenance	6.80	7.06	6.42
Coal	9.26	10.3	9.82
Total	39.3	41.4	39.4
Performance characterization:			
Net output (MWe)	458	456	458
Environmental consequences:			
Offsite solid waste (tons/yr)	3.57×10^4	0	1.65×10^4
Solid waste (tons solids/yr)	1.93×10^5	1.06×10^5	1.10×10^5
Airborne effluents (tons/yr)			
CO ₂	3.36×10^6	3.50×10^6	3.39×10^6
SO ₂	1.89×10^4	1.54×10^4	1.84×10^4
O ₂	5.53×10^5	5.74×10^5	5.60×10^5
N ₂	1.11×10^7	1.14×10^7	1.12×10^7
H ₂ O	1.48×10^6	1.71×10^6	1.27×10^6
Fly ash	2.38×10^2	3.29×10^2	3.85×10^4

^aBased on 7000 hours per year of operation.

^bAll factors are "onsite" unless otherwise noted.

Table 3.20 Critical Factors

Factors	Option I	Option II	Option III
Resource requirements:			
Facility land (acres)	44.2	48.0	45.8
Waste disposal land (acres)	256	142	151
Energy use (electricity + steam) (kWh/yr)	3.55×10^8	3.65×10^8	2.94×10^8
Economic characterization:			
Total capital cost (10^6 \$)	413	426	413
Total electricity cost (mills/kWh)	39.3	41.4	39.4
Environmental consequences:			
SO ₂ (lb/ 10^6 Btu)	1.20	0.936	1.14
Fly ash (lb/ 10^6 Btu)	0.015	0.020	2.38

At this point, Option III can be eliminated for failure to meet the New Source Performance Standard (NSPS) for particulates.* This is due to the fact that no ash removal was performed on the bypassed gas stream. Addition of collection equipment could solve this problem, but would also raise the capital costs and thus worsen the rather marginal cost position of this option.

Of the remaining two options, number I would probably be chosen by most analysts, except for one extremely concerned about land use. The other differences are not significant and the appropriate standards are met in both cases. In retrospect, it appears that the increased capital requirements for burning the western coal more than compensated for the difference in cost of the coal. However, note that the delivered cost of coal is highly location dependent and these results can only be applied to a specific combination of site-mine locations. Also note that no effort was made to analyze the question of scrubber reliability and its effect on operations.

This rather brief trip through the simulation mechanism has illustrated the interplay of modules and the need for consistence in the various factors. It appears that a typical system can be successfully broken down into components such as used here, analyzed, and then reassembled without compromising accuracy. However, it is obvious that any models incorporated into the

*

The existing standards are 1.2 lb/ 10^6 Btu for SO₂ and 0.1 lb/ 10^6 Btu for particulate matter.

system must be carefully studied to insure their technological and economic compatability with other components.

In preparing for future comparisons, emphasis will be placed on refining information related to those modules or factors most heavily influencing the anticipated critical factors. Some effort will also have to be directed toward acquiring up-to-date information for modules not now covered by the program (e.g. coal storage and handling). Finally, the very small differences in the critical factors used in this report emphasizes once again the need for parametric studies on such crucial factors as coal cost.

Other types of factors also need to be considered. The cost of replacing capacity lost to environmental controls should be factored into the total facility cost and a more sophisticated economic approach should be applied. The costs of control systems for water pollution and waste heat disposal must be incorporated into the system and the generation of pollutants offsite should be evaluated. Offsite considerations are particularly significant for distributed systems such as those employing coal washing/flue gas desulfurization combinations.

The ability of this systems approach to reveal synergistic effects will become more apparent as additional technologies are brought into the comparison. For example, it clearly shows that one must consider not only the costs for a given system but also the costs associated with replacing the energy consumed by that system and the additional environmental and social costs incurred in producing that energy. These types of issues will be discussed in future reports in this series.

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