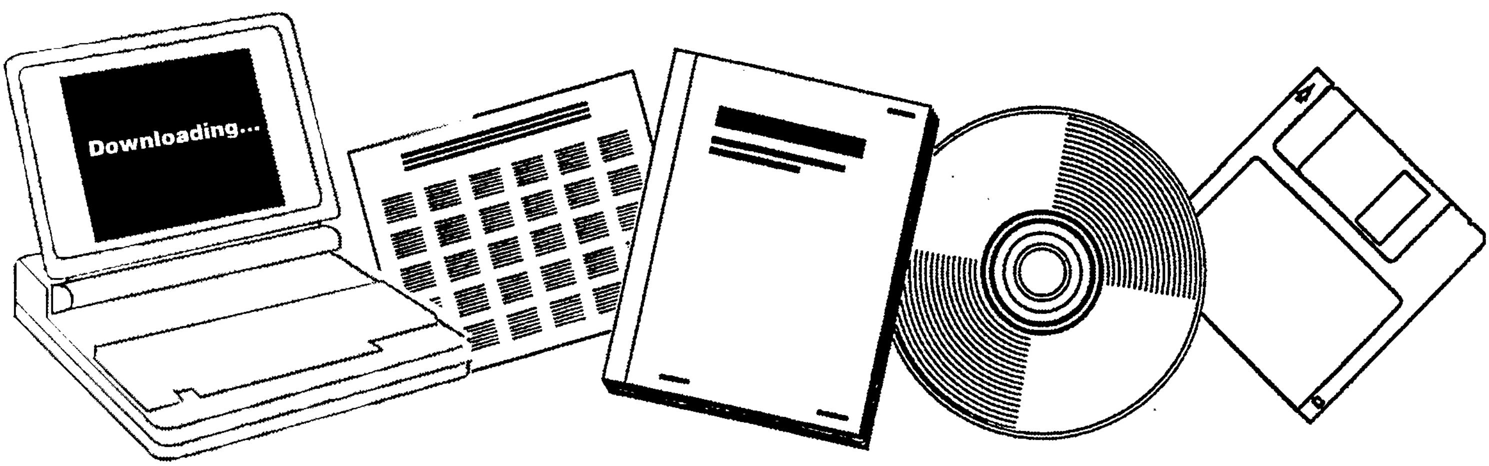
EVALUATION OF COAL CONVERSION PROCESSES TO PROVIDE CLEAN FUELS. PART I

ELECTRIC POWER RESEARCH INST., PALO ALTO, CALIF

FEB 1974



EPRI 206-0-0
Final Report
Part I

EVALUATION OF COAL CONVERSION PROCESSES TO PROVIDE CLEAN FUELS

Final Report

by

Donald L. Katz, Dale E. Briggs,
Edward R. Lady, John E. Powers,
M. Rasin Tek, Brymer Williams,
Walter E. Lobo (Consultant)

Prepared Under Research Project EPRI 206-0-0 by

THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING

For

ELECTRIC POWER RESEARCH INSTITUTE
Palo Alto, California

February 1974

ib

EXECUTIVE SUMMARY

A substantial quantity of high quality research and development has been found in converting coal to clean gaseous and liquid fuels as well as general coal utilization in environmentally acceptable ways. A multitude of organizations in the United States have been working for many years on these processes, some up to 25 years. The variety of programs indicate the complexity of utilizing coal to meet fuel needs and to provide environmental safeguards.

The mix of coal, fuel oil and natural gas presently used, the geographic location of coal supplies and other resource needs relative to plant locations and the variety of processes potentially capable of meeting environmental restrictions, indicate that no single process for coal conversion or use for electric power generation can be expected to be a panacea. Many processes now under development have the potential to reach commercial scale under the right conditions. Research and development support is therefore recommended in fluidized bed combustion, chemical beneficiation, coal gasification and coal liquefaction. Support is encouraged in pyrolysis and insitu combustion.

It should be recognized that the electric power industry's needs for acceptable fuels from coal parallel those of the natural gas industry for high Btu gas production from coal and the petroleum industry for crude oil production from coal. We believe that coal gasification and liquefaction plants will be commercialized and serve the three industries. Fluidized bed boilers, pyrolysis, and chemical beneficiation for certain coals will have their places. Commercial applications are not anticipated before 1980. Research and development which builds upon what is already known and moves in the direction indicated by changing economic and regulatory conditions is vitally needed.

All coal conversion or utilization processes which do not have, at least, short term storage will have potential coupling problems between the fuel production and the power generating system utilizing the fuel. Underground storage of low or intermediate Btu gas, possible in certain geographical locations, could permit independence between those two coupled systems.

Clean low or intermediate Btu gases will be less costly to produce than high Btu substitute natural gas, but because of transportation costs should be produced close to the location of utilization. These gases should be ideal fuels for combined cycle systems.

The overall heat rate from coal to electricity for combined cycle plants fired with coal derived gases or liquids cannot match conventional power plants with stack gas clean-up at present. Combined cycle turbine developments which permit higher operating temperatures could have lower heat rates than conventional plants. Turbine developments are therefore to be encouraged.

Fluidized bed combustion has intriguing possibilities. The boiler installation, itself, should be smaller and less expensive in first cost than conventional boiler installations with or without provisions for sulfur removal. A major problem appears to be the disposal of unused calcined limestone which accompanies the calcium sulfate when limestone is used on a once-through basis. Chemical regeneration of limestone with production of elemental sulfur is many years away from commercial development.

In view of the fact that there are coals available with low organic sulfur and high pyritic sulfur, chemical beneficiation has a place in converting such coals to an acceptable fuel on the basis of sulfur emissions. It would seem worthwhile to develop chemical cleaning systems if they show promise on the basis of reliability and economics.

Finally our study has indicated that there are a number of ancillary problems which are common to many of the systems being proposed for the production of clean coals and work on these should be considered. High priority items are methods of feeding of coal into high pressure systems as a powder or as a slurry, coal slurry pumps, pressure letdown valves for liquids containing solids, high temperature gas particulate cleaning systems, oil-solids separation systems and the production of hydrogen or a hydrogen rich gas from coal, char or coal residue. Control systems should be developed along with the processes to promote safety and reliability.

Our recommendations for research and development support are given in the following table. The recommendations are divided into four categories--fluidized bed combustion, coal gasification, coal dissolution and liquefaction and beneficiation. Work should be supported in each category. The items listed in each category are in the order of endorsement. As in all research and development programs, processes must be regularly evaluated and research management must be prepared to terminate support selectively, where projections are not satisfactory, or where, among competing processes the success of one eliminates need for development of others.

RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT SUPPORT

Fluidized Bed Combustion

1. Support fluidized bed combustion boiler development at atmospheric pressure

2. Support work in disposal of wastes (lime, from fluidized bed combustion)

3. Support research in limestone regeneration

Beneficiation

1. Support the TRW chemical beneficiation process to extract sulfur from pyrite in coal

Coal Gasification

1. Support the Combustion Engineering 120 ton/day atmospheric pressure gasifier pilot project

2. Support the gasification of liquid or solid wastes from coal dissolution processes at pressure in a Koppers-Totzek type gasifier to produce hydrogen for coal liquefaction

3. Support Foster-Wheeler's 1200 ton/day low Btu - combined cycle power generation system

4. Support a molten salt gasification process at pressure

Coal Dissolution and Liquefaction

1. Support the Hydrocarbon Research, Inc. H-Coal ebullating bed, catalytic coal liquefaction process

2. Support continuation of the Wilsonville Process Development unit

3. Support the development of high temperature slurry pumps and pressure let-down methods by equipment manufacturers

TABLE OF CONTENTS

TABLE OF CONTENTS (contd.)

TABLE OF CONTENTS (contd.)

LIST OF TABLES

LIST OF FIGURES

FOREWORD

The Task Force on Coal Utilization of the Electric Power Research Institute approached The University in March 1973 to assess the various processes which convert coal to clean fuels or utilize coal in environmentally acceptable ways for electric power generation. A preliminary proposal was submitted to Mr. Larry Simpkin on March 30, 1973 suggesting a 14-month study. After review and discussion, we were advised that EPRI's need was for a study to be completed by January 1974. Accordingly, the final proposal submitted on June 6, 1973, was for one-half the time and budget originally suggested.

The University of Michigan Team received oral reports on the stages of approval of the proposal and started preliminary studies on July 16, 1973. The Board of Directors of EPRI approved the proposal on August 15, 1973. The final contract agreement was signed by EPRI on October 24, 1973 and by The University on November 13, 1973. A news release, approved by EPRI, was issued by the University on August 24, 1973 and is given on page 58.

The seven-month study was very intensive; members of the team had teaching responsibilities for a substantial fraction of their time during the study in addition to the project work.

The results of the study of coal conversion processes were divided into two volumes: Part I and Parts II and III. In this way, the recommendations for support to the Electric Power Research Institute (Part I) are separate from the critical review and assessment of the coal utilization processes being developed in the nation (Part II).

Part I was prepared specifically to assist the Electric Power Research Institute management in the preparation of a long term research program in coal utilization on behalf of the electric power industry. Part I contains the choices and recommendations for research support by EPRI. Those processes which seem to have the best prerequisites for providing clean fuels from coal at the earliest dates were delineated. The bases for and the reasoning behind the choices are given.

Part II contains the process descriptions and general evaluations of some thirty-seven processes which are reviewed. The team of investigators reviewed and studied reports and research proposals for the processes. Personal visits were made to the organizations carrying out the research and development and to the sites where the experiments are being conducted at bench, process equipment development unit and pilot plant stages. The organizations were very cooperative in providing information and generous with their time in answering our questions. Several organizations provided further supporting information requested by telephone or letter after our visits.

The description of the processes is intended to give members of the electrical utility industry an overall understanding of processes and is not intended to transfer detailed technical knowledge in a thorough manner. References are cited for the more complete descriptions available to the team. It is from those references that the information given has been extracted. The understanding developed by the team and documented in Parts II and III of this report provided the basis for the evaluation rendered in Part I.

Part III contains several topics which are important to coal utilization although not actually coal conversion or utilization processes. These topics were added to give greater perspective to the general subject of coal use.

The authors for the several process descriptions or sections are listed. Dr. D.E. Briggs managed and edited the final report.

Donald L. Katz
February 1973

ACKNOWLEDGMENTS

We acknowledge the time and thoughtful comments freely given by the many individuals in the organizations visited during this project. We appreciate their help sincerely.

We were assisted in this work by the following graduate students in chemical engineering:

Michael W. Britton
Andre W. Furtado
David E. Hammer
Gerald D. Holder
J. Andrew Stirling
Edward E. Timm

We hope their experience has been as interesting as ours.

PART I

EVALUATION OF COAL CONVERSION PROCESSES

EVALUATION OF COAL CONVERSION PROCESSES

The initiation of this project is described in the foreword. The goals of the project were to investigate the ongoing research and development programs on coal conversion to clean fuels and coal utilization in environmentally acceptable ways for electric power generation, and recommend to EPRI those processes whose development warrants acceleration through EPRI's support. The conduct of the investigation is described with some general concepts and observations made during the seven month study.

We were aware that the study of the many processes in seven months would be difficult and that process assessment would often be a matter of judgement. An attempt was made to gather information on basic thermodynamics, rate processes, and chemistry associated with the processes under consideration. To develop some understanding of the processes, flow sheets with process conditions, material and energy balances, results of experimental programs and plans for the future were acquired through reports, papers, interviews and personal visits. Generally, processes go through three or four development stages of increasing size before reaching commercial size. In the early development stage, plans are usually announced for the next larger scale development in proposals soliciting support. Based on the written information gathered and interviews, an assessment was made of 37 processes or topics and is given in Parts II and III of this report, which are bound separately.

The evaluation took into account the nature and requirements of the electric power industry. Factors such as potential cost, efficient fuel utilization, reliability, complexity, environmental considerations and stage of development were therefore of prime importance.

Finally, the various routes, coal beneficiation, gasification, liquefaction and fluidized bed combustion were compared and evaluated with regard to their potential integration into the electric power industry.

It is quite clear in the energy picture that what is done or not done is often more a result of institutional restraints rather than technological developments. Leadership by government and industry in managing these restraints is vital if the technological developments are to serve their intended purposes.

CONDUCT OF THE PROJECT

It was intended that members of the Team would visit the sites of coal conversion projects and interview the investigators. From the general literature, the reports of the Office of Coal Research, and discussions with representatives of EPRI, the principal projects were identified. Before an interview was made at a research and development organization, available reports were reviewed and a check list of needed information prepared.

Table I gives the list of conferences and interviews held. In nearly all cases, the visit was at the site of the development work. Our hosts were very generous with their time, and were helpful in supplying reports and/or added information. A project library was established for making the literature available to the Team for subsequent review.

Members of the Team attended the meetings listed in Table II, at which coal conversion was a significant portion of the program.

A Letter Report was submitted to Dr. R.E. Balzhiser on November 5, 1973 as required by the contract. On November 8, 1973, a meeting with representatives of EPRI and the Task Force on Coal Utilization was held to review progress. On December 14, 1973, the Team met with the full Task Force on Coal Utilization and three members of the EPRI staff. The recommendations by the Team from the study were given orally to representatives of the Task Force on January 10, 1974 along with preliminary draft copies of the final report. Dr. Dale Briggs made a presentation to the Task Force at Atlanta, Georgia on January 16, 1974. These occasions for reporting to the sponsor are listed in Table III.

During the course of this study we also visited organizations and studied processes for which no recommendation is made in this report. There are processes which are well-supported financially and no additional assistance is needed now, and there are processes which have not yet reached the stage where added outside support will speed the development significantly. All processes which have been visited are described to some extent in Part II. There are also several projects which we could not visit owing to the limits on our time. As far as we know, these projects, where publicly supported, will come to the attention of EPRI in the future.

TABLE I

SUMMARY OF INTERVIEWS, SITE VISITS, AND CONFERENCES ON COAL PROCESSING

Organization	Conference Dates	Project Representatives
Air Products	Aug. 16, 1973	Lady, Powers
Atomics International	Oct. 24, 1973	Tek, Williams
Azot Isletmeleri, Kutahya, Turkey	Nov. 1, 1973	Briggs
Battelle, Columbus	Oct. 19, 1973	Briggs, Tek, Williams
Babcock & Wilcox	Oct. 29, 1973	Lady, Lobo, Tek
BCURA Leatherhead, England	Nov. 5, 1973	Briggs
Bituminous Coal Research	Aug. 17, 1973	Briggs, Lady, Powers
Black Mesa Pipeline	Sept. 28, 1973	Katz, Williams
Braun, C.F.	Oct. 25, 1973	Tek, Williams
Brigham Young University	Sept. 22, 1973	Williams
Catalytic, Inc.	Aug. 16, 1973	Lady, Powers
	Sept. 20, 1973	Briggs
Chevron Research	Dec. 3, 1973	Briggs
City College, City University of N.Y. (Arthur Squires)	Jan. 16-17, 1974	Powers
Combustion Engineering	Sept. 25, 1973	Lady, Lobo, Powers
Commonwealth Edison	Aug. 30, 1973	Lady, Powers
Consolidation Coal, Library	Aug. 24, 1973	Briggs, Tek, Williams
Consolidation Coal, Rapid City	Aug. 27, 1973	Lobo, Tek, Williams
Continental Oil Company	Dec. 2-7, 1973	Powers
Exxon	Dec. 17, 1973	Briggs, Katz
FMC	Aug. 7, 1973	Katz, Lady, Powers
Garrett Research	Dec. 2, 1973	Briggs
Gulf Research & Develop.	Oct. 25, 1973	Briggs, Katz
Hydrocarbon Research, Inc.	Sept. 19, 1973	Briggs, Katz
Inst. of Gas Technology	Aug. 22, 1973	Briggs, Tek, Williams

TABLE I (continued)

Organization	Conference Dates	Project Representative
Kellogg, M.W. (Houston)	Oct. 17, 1973	Tek
Koppers	Sept. 28, 1973	Briggs, Lady, Powers
Koppers, Essen, Germany	Oct. 30, 1973	Briggs
National Coal Board, London, England	Nov. 6, 1973	Briggs
Northeast Utilities	Sept. 25, 1973	Lady, Powers
Office of Coal Research (Neal Cochran)	Dec. 19, 1973	Team in Ann Arbor
Oil Shale Corporation	Oct. 19, 1973	Powers
Oklahoma State University	Dec. 2-7, 1973	Powers
Parsons, Ralph M., Co.	Dec. 2, 1973	Briggs
Petroleum Technology	Dec. 2-7, 1973	Powers
Pittsburg & Midway	Aug. 23, 1973	Briggs, Lady
Shell Development	Dec. 2-7, 1973	Powers
Southern Services	Aug. 9, 1973	Briggs
Stearns-Roger, Inc.	Aug. 27, 1973	Briggs, Lobo, Tek, Williams
TRW (Redondo Beach)	Oct. 26, 1973	Tek, Williams
U.S. Bureau of Mines, Bruceton	Oct. 1, 1973 Oct. 24, 1973	Briggs, Lady, Powers Briggs, Katz
U.S. Bureau of Mines, Morgantown	Aug. 1, 1973 Oct. 16, 1973	Briggs Lady, Powers
U.S. Bureau of Mines (Sidney Katell)	Nov. 28, 1973	Team in Ann Arbor
University Engineers	Dec. 2-7, 1973	Powers
University of Utah	Oct. 16, 1973	Katz
Westinghouse	Oct. 2, 1973	Briggs, Lady, Powers
West Virginia University	Oct. 15, 1973	Powers

TABLE II

MEETINGS AND SYMPOSIA ATTENDED WITH PROGRAMS RELEVANT TO STUDY

Aug. 13-14, 1973	EPRI Coal Utilization Meeting, Washington, D.C., (Katz)
Sept. 7-14, 1973	IGT, Clean Fuels from Coal Symposium (Briggs)
Oct. 8, 1973	Canadian Gas Association - Calgary (Katz)
Oct. 29-30, 1973	AGA Symposium on Synthetic Pipeline Gas, Chicago (Katz, Powers)
Nov. 12-14, 1973	AIChE, Philadelphia (Briggs, Katz, Powers, Williams)
Jan. 16-17, 1974	City College, City University of New York (Powers)

TABLE III

REPORTS AND MEETINGS HELD WITH SPONSOR REPRESENTATIVES

Aug. 2, 1973	Meeting of U. of M. EPRI Team with R.E. Balzhiser
Oct. 5, 1973	Meeting with Larry Simpkin
Nov. 5, 1973	Letter Progress Report to R.E. Balzhiser (11 pages)
Nov. 8, 1973	Discussion of Progress Report with George Hill, Larry Simpkin, Jerry Lanzolatta and Kurt Brenner in Ann Arbor
Dec. 14, 1973	Presentation to and discussion with the Task Force on Coal Utilization and with Messrs. Hill, Louks, and Alpert of EPRI, Ann Arbor (28 present)
Jan. 10, 1974	Presentation of recommendations to George Hill and Larry Simpkin, Ann Arbor, Michigan
Jan. 16, 1974	Presentation of final recommendations by Dale E. Briggs, M. Rasin Tek and Brymer Williams, to Task Force on Coal Utilization, Atlanta, Georgia
Jan. 25, 1974	Review of preliminary draft with EPRI staff by Dale E. Briggs, Palo Alto, California

COAL CONVERSION PROCESSES

Coal conversion processes have been evaluated in the major areas shown in Table IV; fluidized bed combustion, beneficiation, pyrolysis, gasification and liquefaction. Figure 1 shows the major areas and comparative information for these areas as they are known to date. An assessment of the major areas, based on reports and interviews, is given in Part II of this report with process descriptions of the processes listed in Table IV. Table V gives a development status of some of the more advanced programs.

The development of some processes is supported by the government directly, for example the Bureau of Mines. Some are part of the natural gas industry's program for substitute natural gas from coal, and others are a part of the general program by petroleum companies to produce liquids from coal. Certain developers have proposals pending or are in process of seeking support. EPRI should sponsor and/or support those processes or programs which offer the greatest potential to the electric power industry and especially those programs which might lag for lack of governmental support.

TABLE IV

COAL CONVERSION PROCESSES REVIEWED FOR EVALUATION

- Fluidized Bed Combustion with Sulfur Removal
  - Pope, Evans and Robbins
  - British Coal Utilization Research Assoc.
  - Esso Research and Engineering
  - Argonne National Laboratory
- Coal Beneficiation for Sulfur Removal
  - TRW's - Meyers Process
  - Syracuse University Process
  - U.S. Bureau of Mines Process
- Pyrolysis
  - FMC - COED
  - Garrett - Flash Pyrolysis
  - Oil Shale Corporation - TOSCOAL
- Coal Gasification
  - Lurgi
  - Koppers-Totzek
  - Winkler
  - Bituminous Coal Research--Bi-Gas
  - Combustion Engineering
  - Foster-Wheeler
  - Atomics International - Molten Salt

TABLE IV (contd.)

M.W. Kellogg - Molten Salt

U.S. Bureau of Mines - Stirred Bed Gasifier

U.S. Bureau of Mines - Synthane

U.S. Bureau of Mines - Hydrane

Battelle - Ash Agglomerating Gasifier

IGT - Ash Agglomerating Gasifier, U-GAS

Squires - Ash Agglomerating Gasifier

IGT - HYGAS

Westinghouse - Advanced Gasifier

Consolidation Coal - CO_2 Acceptor

Brigham Young - Entrained Bed Gasifier

Texaco - Partial Oxidation Process

Shell - Partial Oxidation Process

Bituminous Coal Research - Fluidized Bed

Applied Technology Corp. - ATGAS

U.S. Bureau of Mines - Insitu Combustion

Coal Dissolution and Liquefaction

Hydrocarbon Research, Inc. - H-Coal

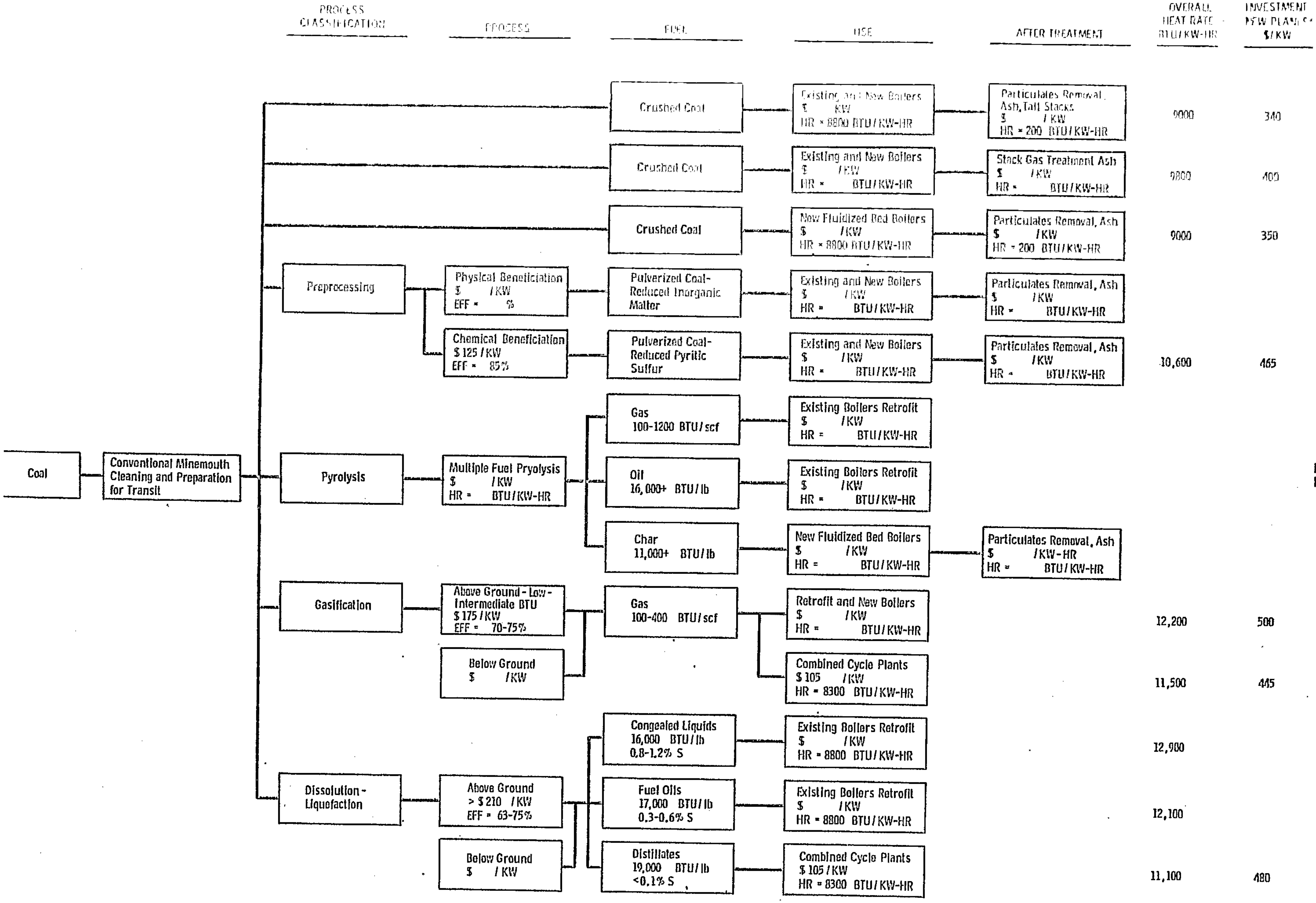
Pittsburgh & Midway Coal Mining Company - Solvent Refined Coal

Southern Services, Inc. - Solvent Refined Coal

Gulf R & D - Gulf Catalytic Coal Liquids

U.S. Bureau of Mines - Synthoil

Consolidation Coal Co. - Consol Synthetic Fuel



* Includes $165/KW for construction, site preparation, interest, contingencies, buildings, cooling towers, etc.

Figure 1. Alternate Routes to Coal Utilization for Electric Power Production

TABLE V. CLEAN FUEL PROCESS DEVELOPMENT PROGRAMS

PROCESS	TYPE	NOTES	SCALE	SIZE T/D	1960	1965	1970	1972	73	74	75	76	77	78	79	80	81
Applied Technology (Atgas)	Gasif.		Bench Pedu	~ ~					D	C O							
Bureau of Mines (Stirred Bed)	Gasif.		Pedu	10													
Battelle	Gasif.		Bench Pilot	~ 2.5					D&C		O						
BCR BI-Gas	Gasif.		Bench Pedu Pilot	0.1 1 120					C	O							
Brigham Young Univ. of Utah	Gasif.		Bench Pedu	~ 1					D	C	O						
Consol Coal CO_2 Acceptor	Gasif.		Bench Pilot	~ 50			C		O								
Combustion Engineering	Gasif.	(1)	Pilot Pioneer	120 2000				D									
Exxon	Gasif.		Bench Pioneer	0.5 400				O D									
Foster Wheeler (et al.)	Gasif.	(1)	Pioneer	1200					D		C	O					
Hydrane	Gasif.		Bench	~													

TABLE V. CLEAN FUEL PROCESS DEVELOPMENT PROGRAMS (contd.)

PROCESS	TYPE	NOTES	SCALE	SIZE T/D	1960	1965	1970	1972	73	74	75	76	77	78	79	80	81
IGT Hygas	High Btu Gasif.		Bench	~													
			Pilot	75				O									
Koppers-Totzek	Gasif.	(2)	Comm.	~													
Lurgi	Gasif.	(2)	Comm.	~						D&C							
Molten Salt (Atomics International)	Gasif.		Bench	~													
			Pilot	120/240						D							
			Pioneer	2400													
Molten Salt (M.W. Kellogg)	Gasif.		Bench	~													
Bureau of Mines Synthane	Gasif.		Bench	1<													
			Pilot	75													
Westinghouse Bechtel et al.	Gasif.		Pedu	4					D&C	O							
			Pilot	120								D,C&O					
			Pioneer	1200									D		C	O	
IGT, U-Gas	Gasif.	(3)	Pioneer	1000													
Gulf Catalytic Liquefaction	Liq.			1						D&C	O						
				500						D	C			O			
				1500						D					O		
H Coal	Liq		Pedu	3			DC&O										
				700					D								

TABLE V. CLEAN FUEL PROCESS DEVELOPMENT PROGRAMS (contd.)

PROCESS	TYPE	NOTES	SCALE	SIZE T/D	1960	1965	1970	1972	73	74	75	76	77	78	79	80	81
Pittsburg & Midway	Solv. Refin.		Bench Pilot	~ 50		D		C		O							
TRW Systems	Chem. Ben.		Bench Pilot Pioneer	~ 12 10,000													
FMC Corp. Coed-Cogas	Pyrol.		Pedu Pilot	1 36													
Exxon	Fluid Comb.																
Pope, Evans, & Robbins Foster Wheeler	Fluid Comb.		Pedu Pilot Comm.							C D	O C	O					
C.F. Braun	Study	(4)															

——— Firm Plans
– – – – Proposal
D-Design of Plant
C-Construction of Plant
O-Operation

NOTES: (1) Basic Data from BCR PEDU
(2) Koppers-Totzek and Lurgi Processes are Commercially Available
(3) Conceptual Design Underway Based on IGT DATA
(4) C.F. Braun is Evaluating Processes for High BTU Gas Production

BASES FOR COMPARISONS OF PROCESSES FOR CLEAN FUELS

The electric power industry has diverse equipment and fuel requirements in spite of a common product. Geographic location in relation to raw fuel supplies and waste disposal, and retrofit, environmental and load factor considerations suggest that beneficiation, fluidized bed combustion, coal gasification and coal liquefaction can all serve the utility industry. Research and development are therefore recommended in each area.

In assessing the processes in each area, several factors were considered. These include:

Present scale, scale-up and time to commercial operation

Complexity, reliability, and safety

Adaptability to utility use

Turn-down

Thermodynamic efficiency

Environmental considerations

Economic evaluation

Judgement

Comparison to stack gas cleaning

Based on these factors, recommendations were made for support in each area. The recommendations in each area are given in order of priority in the "Evaluation of Various Routes to Clean Fuels and Recommendations" section of this report.

Scale-up and Time to Commercial Operation

An important consideration in choosing processes for further development is the time still needed to reach reliable, commercial operation. Developments usually proceed in the order; bench scale (~100 lbs/day), process equipment development unit (~1000 lbs/day), pilot unit (25-75 tons/day), demonstration plant (500-2000 tons/day), pioneer plant (first of a kind at near commercial scale) and commercial scale plant (10,000-25,000 tons/day). With one to three years required for each step, the time to reach commercial scale can be lengthy. In some cases, it has been suggested that certain development steps be omitted. The larger scale-up requirements are not nearly so risky when based on comparable processing steps in other industrial operations.

Table V summarizes the projected time schedule for the major processes as obtained from research and development proposals, and interviews with project developers. The time schedules are subject to the usual delays. Many of those processes with success in early or intermediate stages could have a pioneer or demonstration plant within five to ten years, given normal economic conditions.

It is clear from this study that few demonstration or pioneer scale units will be operating within five years under normal procurement and the R & D conditions prevailing today.

Complexity, Reliability and Safety

Evaluation of processes from the viewpoint of complexity is difficult since there are so many factors involved. Items which add to the complexity are the number of processing steps, the operating pressure and temperature, the sensitivity to changes in temperature, solids recirculation, moving parts at high temperature, corrosion, and the need for auxiliary process plants.

The complexity and the capital cost of a process is related to the number of processing steps or pieces of process equipment needed. When a process contains several pieces of equipment which have a tendency to fail, the process reliability would be of concern because of the probability for failure.

The TRW chemical beneficiation process, the molten salt processes and the COED pyrolysis process have several process steps. Although many of the steps are related to current technology, operations with coal or mineral matter in coal tend to complicate each step.

Reliability becomes more of a concern at high pressures and temperatures especially if there are moving parts. Coal dissolution processes operate at fairly high pressures. All need pumps and pressure let-down systems and a few incorporate filtration into the process. Although coal gasifiers do not need to operate at particularly high pressures (usually less than 300 psi), lock hoppers would be required for pressures in excess of 20-30 psig.

The metal walls of reactor vessels must be protected from high temperatures and corrosion. This is usually accomplished by covering the inside surface with an insulating material and a ceramic lining, or by cooling the walls with water. All the coal gasifiers use one method or the other.

The mineral matter in the coal puts temperature limits on gasification and pyrolysis. Gasifiers can operate below the ash fusion temperature, near the fusion temperature as in ash-agglomerating gasifiers or above the slagging temperature. The ash-agglomerating gasifiers depend upon operating at temperatures where the ash is slightly tacky but not fluid. Such systems are sensitive to temperature variations and the mineral content of the coal.

Recirculation and movement of solids is common to many of the gasifier and pyrolysis processes. Control of such movement adds to the complexity.

Auxiliary process plants are needed in many of the processes. The coal dissolution processes require hydrogen production. Many of the gasifier processes use oxygen although air can often be used with a reduction in heating value of the product. Auxiliary equipment adds to the complexity of the total process.

Safety considerations are of great importance and appear to have been incorporated into all the processes. However, problems may be expected with high pressures and temperatures, gas leakage, flow and combustion instabilities, start-up and shut-down procedures, controls and instrumentation. Only long term, full scale plant operational experience will permit the safety aspects to be fully known. Despite the best engineering judgement in the design of new plants, a certain safety risk factor must be assessed to all untested processes. This risk is in proportion to the pressure, temperature, reaction rates, and size of the project and inversely proportional to the amount of actual operational experience of identical or very similar processes.

In gasification the greatest hazard occurs when a coal or char supply to the gasifier is interrupted but the air or oxygen flow continues. This is most serious in an entrained flow gasifier when the coal hold-up is small and there is potential for oxygen to mix with the synthesis gas. In the Koppers-Totzek gasifier the oxygen supply is automatically shut off when the coal supply is interrupted and either nitrogen or steam used to purge the system. Similar safety interlocks would be required for all entrained flow gasifiers.

When looked at from the viewpoint of simplicity, reliability and safety, the fluidized bed boiler and the atmospheric pressure entrained flow gasifier appear to be the most suitable for incorporation into electric utility power generation plants.

Adaptability to Utility Use

To a great measure, the success or acceptance of a new process depends upon the adaptability of the process to the unique requirements of the particular utility plant, or the plant site to be served.

In retrofit applications, system derating is an important consideration. Boilers designed for gas and oil cannot be converted to coal without substantial derating. Intermediate Btu synthesis gas from oxygen blown coal gasifiers and coal derived liquids can be used in these boilers with little or no derating although some changes in heat transfer surface may be required. The use of low Btu synthesis gas from air blown gasifiers will result in some derating of boilers designed for oil and gas. Boiler modifications can minimize the extent of the derating.

The intended load application of the power operating system influences the suitability and cost of coal conversion processes. Those which produce a fuel capable of being stored economically have an inherent advantage for intermediate and peak shaving load applications and load following. In certain geographic locations underground storage of intermediate Btu gas makes coal gasification processes attractive.

The location, availability and characteristics of the coal and raw materials such as limestone become important in the selection of a coal conversion process. Certain coals can be used in certain processes and not at all in others. Waste disposal must also be considered.

Control of a fuel generating system coupled to an electric power generating system requires special attention. Hopefully, experience and understanding will result from the Commonwealth Edison - Lurgi program.

Turn-down

The question of turn-down capacity of the various clean fuel processes have been considered as a factor of importance in meeting the daily load variation of the electric utility industry. It is generally felt that such processes will be widely used for intermediate load applications. All processes which produce a clean, storable fuel are not tightly linked to this daily load cycle and therefore can be run at design conditions under steady 24-hour per day operation. These include: chemical cleaning of coal, coal liquefaction and pyrolysis-based coal refineries. This becomes important when considering the effective capital cost for a front-end clean fuel system used for intermediate or peak load applications. For a 50% electrical load capacity factor the cost of the clean fuel process with storage would be nearly one-half the cost of a plant for base load application.

There will be more problems associated with storing pyrolysis char than coal but it can be stored. Pyrolysis chars tend to be dusty and pyrophoric. Only in certain geographic locations will underground storage of low or intermediate Btu gas be economically and physically feasible. Intermediate Btu gas would be preferred.

Two considerations are important: capacity variation from 100% to some lowest limit and start-stop-start capability. In general fixed-bed gasifiers such as the Lurgi and U.S. Bureau of Mines stirred-bed units are easiest to operate and operate well over a wide range. They can be kept in a banked condition overnight with the natural draft aspiration of air creating enough heat to maintain bed temperatures. Entrained flow gasifiers can be operated at 50% of design rating in analogous boiler technology. Start up of these units is somewhat complex, usually requiring gaseous or liquid fuel firing and bypassing or venting initial gas production. Fluidized bed processes require gas flow for fluidization. They can be turned down to 50% or less capacity without problems. As the load decreases, the bed porosity decreases and approaches a fixed bed gasifier at low gas flow rates.

Most gasification processes require gas clean-up trains for H_2S and particulate removal. These are based on conventional chemical processing technology and turn-down to 50% should represent no special problem, providing consideration is given to this in the design stage. Start-up and shut down of these chemical processing trains will not be a reasonable daily operating procedure. It would be preferable if such processes operated continuously, with maximum turn-down of 50%. Daily electric load variations must be accomodated by other means (pumped-storage, intermittent operation of older plants, partial turn-down of base load units) rather than daily start-up and shut down of complex chemical processes.

Thermodynamic Efficiency

The customary expression of efficiency used by the utility industry is the heat rate--that is, the energy input to the system as gross heating value of the fuel required to produce one kilowatt hour of electrical energy (Btu/kilowatt hour). When comparing processes and raw materials or plants, it is vital that the total system be properly defined and all energy demands be included. In comparing oil fired to coal-fired plants,the energy necessary to grind and inject coal must be included as must oil pumping costs. In evaluating gasification processes, the energy needed to supply air or oxygen, cooling water,steam, briquetting operations and so forth must be included in the accounting. Similarly, material balances must include all streams in and out.

In this study, it was frequently impossible to determine overall thermal efficiencies of processes from reports because of unreported data on inputs or output streams. Where enough information was available thermal efficiencies and/or heat rates were determined and included in Figure 1 and in the process descriptions.

A refinement possible in the thermodynamic efficiency is the use of the second law of thermodynamics to compute entropy production. This will be especially useful where there are multiple products from the process. Development of this type of analysis is a prospect for the future, and detailed procedures are described in Part III.

Environmental Considerations

The primary objective of coal conversion processes is to utilize coal in ways such that the emission of sulfur, nitrogen and hydrocarbon compounds and particulates are environmentally acceptable. This includes discharges of gases, liquids and solids.

It is expected that many processes have the potential to reduce emissions well below EPA requirements. Where much lower emissions can be realized at minimal additional costs, it is reasonable to expect that such additional costs be paid.

The technology of hydrogen sulfide removal from gases at, somewhat above, and below ambient temperatures is well established. Thermodynamic efficiencies would improve if high temperature hydrogen sulfide removal systems could be developed for commercial application. It would also be important that the nitrogen compounds such as ammonia be removed since such compounds are commonly converted to the oxides of nitrogen upon subsequent combustion.

Gas liquors from gasification and liquefaction processes constitute a water pollution problem. Treatment of such water waste streams will be required. Gasification processes which operate at high enough temperatures to crack oils and tars have a distinct advantage over other processes. Ammonia could still be a problem.

In coal liquefaction processes water will appear in the light gas oil condensate. The water is from the original coal or from hydrogenation of the oxygen in the original coal. Water wastes must be treated prior to discharge into the environment.

Solid wastes become troublesome when they contain leachable components in measurable amounts. This is especially true when limestone is used and calcium oxide is formed or where the coal ash has unique qualities.

Front-end clean fuel processes will reduce the amounts of heavy metals discharged to the atmosphere because of gas clean-up.

Economic Evaluation

In these days of uncertainties in cost of constructing plants, cost forecasting is no occupation for the timid. Economic evaluations were made based on the best information available to the team. No claim for accuracy is made. It is believed, however, that the relative costs are sufficient to give perspective to the various routes of coal utilization.

Since each of these processes uses raw energy with some inefficiency, it should be clear that the cost of the raw fuel itself becomes a factor in the operating cost.

A write-up is included in Part III of the report which discusses economics and the method of evaluating and comparing processes based on the Federal Power Commission procedure. The opportunity to carry out full economic comparisons was not possible because of the lack of hard information and sufficient time. Economic information reported is that provided to the study Team by process proponents rather than by independent calculations.

The general routes to the use of coal for electric power generation are shown in Figure 1. The costs in $/KW and thermal efficiences or energy penalties in Btu/KW-HR are given where estimates can be made at this time. The costs cannot be considered firm because of the conditions under which the diverse economic studies were made. Studies have been made by proponents of the processes at an early stage of development. Studies have also been made by independent engineering organizations with limited data in times of material shortages and inflation. The relative costs of routes are believed to be representative in comparing cost differences between alternative routes.

Thermal efficiencies listed in Figure 1 are representative of values capable of being realized at present.

As a basis for comparison, the overall investment cost and the heat rate for a new conventional power plant are taken as $340/KW and 9000 Btu/KW-HR respectively. This includes the cost and energy penalty associated with particulates removal and ash handling. The additional cost and energy penalty associated with stack gas clean-up are taken as $60/KW and 800 Btu/KW-HR. These values are consistent with current information. Of the $340/KW, the overall investment includes $165/KW for construction, site preparation, interest, contingencies, buildings, cooling towers and related items.

Based on the many cost values which have been presented by various sources, the following is a list we believe valid for the processes in the order of increasing cost of new installations operated with coal to produce electricity for base load:

Conventional plant with tall stack
Fluidized bed combustion
Conventional boiler with stack gas cleaning
Coal gasification with combined cycle
Chemical beneficiation
Coal liquefaction with combined cycle
Coal liquefaction with conventional plants

This is reflected in Figure 1 where costs are given in $/KW. As the application shifts from base to intermediate or peak-shaving load applications, the coal liquefaction and beneficiation processes which produce storable products tend to become competitive with the less expensive processes.

The capital cost impact clearly depends upon application. For intermediate or peaking load, a combined cycle plant with clean fuel derived from coal may be competitive with conventional plants because of the lower heat rates of the combined cycle and the lower electric power generating costs. To take advantage of this aspect it is necessary to operate a small fuel generating plant at or near maximum capacity and store the extra fuel production for peak-shaving. Liquid fuels look attractive for such applications. Low or intermediate Btu fuels could be attractive where inexpensive underground storage could be made available.

The thermal efficiencies of the front-end clean fuel from coal processes range from 65-85%. As a consequence, the overall heat rate from coal to electric power which incorporates a front-end process will be in the range of 11,000-13,000 Btu/KW-HR. In periods of coal shortages and rising costs, energy conservation become extremely important. At heat rates of 9000-10,000 Btu/KW-HR, stack gas cleaning and fluidized combustion boilers look attractive.

Combined cycle plants with a somewhat higher efficiency than a conventional system today, tend to off-set the penalties associated with front-end clean-up. For a gasifier efficiency of 75%, the heat rate of the combined cycle portion of the plant would have to decrease from the present value of some 8300 Btu/KW-HR to 7350 Btu/KW-HR before the overall system heat rate could match plants with stack gas clean-up. Potential improvements of this magnitude are not likely in the next decade.

Costs of several processes are available as preliminary estimates for commercial plants. These specific costs are included in the sections on gasification, liquefaction, and chemical beneficiation and should be used knowing their character.

On Figure 1, the $/KW are given as judgement values.

Judgement

After economic considerations, it is judgement or the composite assessment of all non-economic criteria which leads to a final evaluation of a process. Judgement calls heavily on experience when many of the criteria cannot be assessed for lack of information or data.

Comparison to Stack Gas Cleaning

Processes for removing sulfur from coal before or during combustion could well be so costly and lack assurance of being reliable for continuous operation that stack gas cleaning in spite of its drawbacks and frustrations may well be cheaper than and no worse operationally than producing clean fuels from coal.

In this study, processes were evaluated keeping in mind that they would have to be potentially better than stack gas cleaning processes to be considered as a viable alternative.

An evaluation of stack gas clean-up was not in the scope of this study. However, a brief statement is included to give perspective to the alternate way of removing sulfur in coal--after combustion. The reader is referred to the report by Falkenberry and Weir which presents the status of stack gas clean-up as the method of meeting emission standards and to the SOCTAP report sponsored by EPA.

From these studies one would conclude that the cost of new stack gas cleaning systems will range from $50-80/KW and retrofit installations will be considerably higher.

Statements could be included about the operational aspects of stack gas cleaning processes, but the recipients of this report already have such information.

The energy penalty associated with stack gas cleaning ranges from 2-8% depending upon the process and reheat requirements. Front-end coal conversion processes are likely to have a penalty range from 15 to 35%.

When front-end sulfur removal processes are assessed with respect to costs, costs are found to be high relative to stack gas cleaning. The stage of development and the time needed before front-end processes are available and reliable, indicates that stack gas cleaning may have relative merits.

GENERAL OBSERVATIONS

This study has exposed the Team to many related areas concerned with energy and the environment and to many people of different viewpoints and opinions. Much of this exposure was outside the immediate objectives of this study but is of such importance as to warrant mention.

Institutional Restraints

The development and success of a process to provide clean fuels from coal and the effort required to attain commercial operation depends upon factors outside technology as well as in. The factors were called institutional restraints in the Saxton River sessions on Energy Technologies for the Future. Restraints can help and hinder development. The electric power industry through the Electric Power Research Institute could well join others in concerted efforts to speed up rational action in making coal available and converting it to an acceptable fuel.

Common Interests with Gas and Oil Industries

The electric power industry has needs parallel to the natural gas industry and the petroleum industry in providing fuels from coal. The research and development program sponsored by the American Gas Association and the Office of Coal Research to produce pipe-line quality gas from coal as a substitute natural gas was recognized as a significant contribution to the electric power industry. Many of the coal gasification processes could be used to produce low or intermediate Btu gas where high heating values are unwarranted for utility fuels. In other cases, new gasifier concepts were developed based on research and development in the high Btu gas program.

The ultimate need to produce synthetic crude oil from coal has been a concern of both government and petroleum companies. When the need arose for clean, low sulfur coal liquids for utility plants, work was already underway. Fuel oil desulfurization research and experience in building and operating desulfurization processes in the petroleum industry lends assistance to coal liquefaction process development.

It appears that the future plans for coal liquids go more to coal refineries than to plants built specifically for utility plants and utility operation. Thus for steam generation, use of the lower grade by-products of coal refineries may be best. Both avenues should be kept in mind. In any event, the impetus to produce crude oil is compatible with the need for low sulfur utility fuels.

It is expected that the petroleum industry will develop coal refineries or coal pyrolysis processes with multiple subprocesses and a series of products including low to high Btu gas, a series of fuel oils, and char. It is expected that certain products will be produced for combined cycle turbine fuels. Residual oils will be used as they are today for steam generation. The utility may well be expected to accept the burden of utilizing the char.

Need for National Priorities and Allocations

As one looks to the time schedule for building the process development units, pilot, and demonstration plants and sees a decade of time consumed in the sequence, one questions today's pace as compared to those in the 1940's for the development of aviation gasoline, synthetic rubber, U-235 and other commodities. No doubt the desire of the public to achieve those goals was most important, but the use of engineering judgement and willingness to take risks financed by the government was another factor. A third factor which is now seen in the energy crisis and is being felt today is priority for delivery of equipment and supply of services of skilled people.

EPRI might well join with other groups like the API, AGA, EJC, Labor Unions, and others in sponsoring methods to assure the availability of steel, equipment, engineers, scientists, skilled trades, and enabling legislation for developing coal conversion processes as well as nuclear facilities.

University and Institute Support

Manpower needs for coal conversion processes require increased enrollment and graduate study in several branches of engineering and science. Graduate study can serve the utility industry in two ways: providing highly trained technical personnel, and in developing technical knowledge needed.

The support of university work should be directed toward the objectives of increasing the available pool of engineers and scientists who are competent and interested in the problems of the utility industry, and of increasing knowledge and understanding of coal and coal processing. The nature of university research is that it is well-suited to the formulation of information and novel ideas which can improve the next generation of processing and design, and in certain areas to the solution of immediate problems.

Some subjects which are adaptable to the pace and scope of university work are: fundamental work on all properties of coal, mechanisms and kinetics of coal processing, studies in peripheral subjects such as disposal or recovery of waste materials like calcium sulfate, underground storage of low Btu gas for intermediate and peak-shaving loads, catalyst development, process design and feasibility studies of new and novel ideas, meteorological studies of air quality impact, plant and wild-life problems associated with mining facilities.

Major non-profit research institutes have and will continue to make important contributions, and also represent a pool of experienced engineers and scientists. In general, their work seems to fall in the area between university-type research and full-scale industrial work, but often overlapping both. Support of work at such institutes and cooperation with them should enhance the use of EPRI resources.

Attention to Coal Mining

Increased usage of coals for utility boiler plants as well as for providing replacements for natural gas and crude oil will require substantial increases in coal mining. Automated mine development was recommended in the Saxton River Conference to reduce the need for underground workmen. The adoption of higher standards for mine safety has decreased output per man-day for underground mines. Attention to mining technology comparable to that required to put a man in space seems reasonable and advocacy of such support by customers for coal, like the utility industry, seems justified.

Another problem in public view is resistance to strip mining of coal, based in good part on past practices in which damage to the environment is evident today. Management of acceptable methods of strip mining and education of the public on what can be done could remove a severe road block to increased coal production by strip mining in the years ahead.

Consideration of Tall Stacks

If acceptable commercial clean fuel from coal processes and reliable stack gas cleaning systems do not come into being in the short term, it may be necessary to resort to tall stacks under certain conditions to protect our natural gas and oil supplies. One way to operate on high sulfur coals with reduced environmental effects, is to use smoke stacks which are 1000-1200 feet tall and rely on dispersion. This approach has been used in England and the ground level air quality has been improved significantly over the past two decades. Granted, this is not an ideal solution but would provide time for a more rational development of coal conversion technology.

EVALUATION OF VARIOUS ROUTES TO CLEAN FUELS AND RECOMMENDATIONS

Fluidized Bed Boilers

The concept of fluidized bed combustion boilers has been advanced recently by research in England, France and the United States. Fluidized beds which utilize limestone (atmospheric pressure) or dolomite (pressurized) provide for sulfur removal within the combustion chamber. As developed by Pope, Evans and Robbins and Foster Wheeler, the fluidized bed boiler has the merit of modular construction and a high heat release rate and thus a reduced volume combustion chamber. The possibility of economical steam generation at lower investment costs than by conventional plants seems real.

The handling of the solid waste, containing sulfur as $CaSO_4$ has been studied by Esso and Argonne, both looking to recovering elemental sulfur and recycling the calcium to reduce raw material requirements. Regeneration processes for a demonstration or commercial size plant are about a decade away.

Operation with limestone on a once-through basis creates solid waste problems. Even though $CaSO_4$ supposedly encapsulates the CaO , judgement would indicate that the solid would be subject to dissolution by ground water in land fill areas. The $Ca(OH)_2$ produced by hydration of unreacted CaO has a solubility limit of 0.18% by weight in cold water and fresh $CaSO_4$ has a solubility of 0.2%. Carbon dioxide from the air would eventually convert the hydroxide to carbonate. Flue gas could be used to facilitate this conversion. Therefore, an air pollution problem has been converted to a potential water pollution problem. Accordingly the recommendations include research on handling the lime in the waste as well as sulfur recovery as a priority item . The fluidized bed boiler has sufficient merit as a steam generator to warrant support even though solution to the chemical problems are in the early stages of development.

Recommendations for research and development support in fluidized bed combustion are:

The Fluidized Bed Boiler is recommended for support because of the dual role it can play of giving economical compact units for steam generation at atmospheric or pressurized conditions. It also can remove sulfur during the combustion process by using limestone or dolomite as the fluidized bed.

A Process for Handling the Lime Waste should be developed for a once-through process. Laboratory work, process development and environmental studies should be made to handle the disposal of this waste until economical regeneration processes are developed.

Coal Beneficiation

The physical cleaning of coal involves crushing, grinding, sizing, solid separation, washing and flotation in various combinations designed to reduce inorganic matter. A new process for removing pyritic sulfur by stage-wise froth flotation was recently announced. Recently, chemically induced breakage (comminution) using methanol and ammonia gained some interest through research conducted in Syracuse Research Laboratories. The coals which have been processed by physical beneficiation must satisfy the usual pulverized boiler feed and environmental sulfur emission requirements.

As compared to physical treatment described above, chemical beneficiation goes a step further in that chemicals are used to remove the pyritic sulfur from the coal. For coals with low enough organic sulfur, this beneficiation is designed to make those coals suitable for meeting environmental regulations. Chemical beneficiation is purported to remove up to 90-95% of pyritic sulfur and lose not more than 5% of the coal while current physical cleaning processes remove about 50% of pyritic sulfur and to lose not more than 5% of the Meyers Process developed by TRW has had bench scale (5 liter) extraction tests with ferric sulfate [Fe_2 $(SO_4)_3$] as a solvent on four typical Appalachian coals. Based on bench-scale and pre-pilot test data, engineering design and cost estimate studies have been under way for a process plant to treat 10,000 tons of coal per day.

Disposal of solid and liquid wastes from this process represents serious environmental problems. This aspect must receive at least as much attention as the disposal of CaO from fluidized bed combustion with limestone.

Recommendation for research and development support in beneficiation is:

Support the TRW - Meyers Small Scale Pilot Plant to convert some high sulfur coals into coals which meet environmental regulations for sulfur. If further data reinforce present views, demonstration plant support would be appropriate. It is noted that the process uses processing steps based on current technology and may be more predictable in scale-up than processes with much new technology. Attention to waste streams is essential.

Pyrolysis

The pyrolysis processes reviewed were the COED, TOSCOAL and Garrett flash pyrolysis processes. These processes yield low to high Btu gases, liquids and char. The gas can be treated to remove sulfur and the oil hydrogenated to lower the sulfur content and the oil viscosity. Chars from the pyrolysis of high sulfur coal will contain too much sulfur for burning in conventional boilers and must be utilized in fluidized boilers or as feed for gasification.

It appears that pyrolysis is more adapted to the concept of a coal refinery than to a captive fuel plant for electric power generation. A refinery could contain several coal pyrolysis units and the light desulfurized liquids or gases would be suitable for combined cycle operation. Also, some of the heavier oil fractions could become clean economical boiler fuels. Char containing sulfur would be available for utility use but would have the same problems as high sulfur coals.

It should be recognized that the COED process has considerable operating experience at 36 tons/day and is a near atmospheric pressure process for clean gas and oil production. Advantages are claimed for char as feed to gasifiers. It is non-caking, gives off no tars, and is claimed to have a high reactivity with oxygen and steam especially when hot. When these benefits and/or the desulfurization of char has been demonstrated, the COED pyrolysis process has the ability to produce fuels for gas turbines in the combined cycle as well as boiler fuel with both the liquid and char in form for storage.

The TOSCOAL process is based on the oil shale retorting procedures developed by the Shale Oil Corporation in their TOSCO process. Coal has been retorted at a rate of 24 tons/day. In a demonstration unit, oil shale has been retorted at a rate of 1000 tons/day and coal could be retorted.

It is recommended that when utility plants desire both combined cycle and boiler firing fuels, the pyrolysis processes merit consideration. The gasification of char with desulfurization of the fuel gas is the next step in the COED development, and should be given consideration because of the advanced state of the pyrolysis technology.

Coal Gasification

Commercial low-to-intermediate Btu coal gasification processes are currently available today through Lurgi and Koppers. They represent two diverse methods of gasification being fixed-bed and slagging entrained-flow gasifiers, respectively. The Lurgi gasifier is limited to non-caking coals at this time. The Winkler fluidized bed gasifier is also available. It is limited to non-caking coals. To date there has been no experience in coupling a gasifier system to a conventional power plant or a combined cycle plant. Control experience for such systems is needed. Capital cost of the available intermediate Btu gasifier systems is believed to be about $170-$180/KW and the thermal efficiency is about 70%.

Coal gasification processes find their greatest opportunities in conjunction with combined cycle plants. The higher thermodynamic efficiency of such combined plants tend to offset the energy lost in gasification. It will be several years before the overall thermal efficiency matches that of a conventional plant.

Developments through the pilot plant scale in this country have evolved from the Lurgi and Koppers-Totzek gasifiers. The work is directed toward the capital cost reduction and the thermal efficiency improvements which are theoretically possible. It does not appear likely that commercial-size plants will be operating however before the 1980's based on these developments.

Low and intermediate Btu gasification processes must be located at or near the electric power plant because of the expense in transporting lower Btu gases. It is expected that coal gasifiers will have to follow load. Storage costs would be excessive except perhaps where underground storage is available. From an economic standpoint, base-load operations would be preferred since the gasification plant capacity must match the electric power generating capacity.

Coal gasification systems vary in complexity, start-up and shut down capability and turn-down. Unless the process is simple, reliable and amenable to control, it will be difficult to couple to an electric power generation system. Turn-down of 50% for individual gasifiers seems likely for most systems. Environmental problems should be minimal.

The Combustion Engineering atmospheric two-stage slagging entrained flow gasifier concept is reasonable, simple, offers minimum development problems and is directed toward reducing or eliminating the oxygen requirements of a Koppers-Totzek gasifier. Support for this program is therefore recommended.

Foster Wheeler has proposed a demonstration size plant. Although proven equipment is employed where possible, it represents a bold effort. The gasifier would be conceptually similar to the Bi-Gas and Combustion Engineering gasifier and would operate at 500 psi.

The process analysis based on laboratory data shows that molten salt gasification and desulfurization has a possibility of low cost and simple construction. Salt regeneration is based on known technology although the ash is a definite complication. The process is worth support through the next step of development to evaluate its feasibility.

Recommendations for research and development support for coal gasification are:

The Combustion Engineering low pressure proposal should be supported. We believe the entrained flow slagging gasifier, blown with air, has the potential to reach commercial scale in conjunction with combined cycle plants. The operation draws upon the experience of reputable boiler manufacturers. It speaks to the critical development steps while eliminating the complexity of operating at high pressures in the early development stage. The concept includes sub-processing steps which are available commercially.

Hydrogen production by a Single Stage Slagging Gasifier for hydrogen production is needed. A process which is economical and utilizes debris of liquefaction processes should be developed for the coal dissolution processes. A hydrogen generation unit should be incorporated into a dissolution process, with candidates recommended: Koppers-Totzek, Texaco or Shell gasifier processes.

The Foster Wheeler High Pressure Coal Gasification approach is comparable to that of Combustion Engineering except that it is directed toward high pressure operation from the beginning. High pressure (100-300 psi) gasification is preferable for combined cycle application. The Foster Wheeler approach is bold to the extent of size and pressure but if successful could cut out many years of development in reaching commercial scale, and should be supported.

Molten Salt Gasification is a novel method of gasification and deserves support. This process is attractive since it incorporates desulfurization with gasification and lends itself to potential thermal efficiency improvements. Salt regeneration is complicated but based on established commercial technology in the paper industry.

Coal Dissolution and Liquefaction

Coal liquefaction processes have been under development since the late 1950's and have progressed through the process development unit size of 1-3 tons coal/day. The work draws upon the technology of fuel oil desulfurization and except for the coal solution and solids-separation steps lends itself to the scale-up procedures practiced by the petroleum industry. From our study we conclude that the Hydrocarbon Research, Inc. single step catalytic coal dissolution and desulfurization (and denitrogenization) process offers the best potential to reach commercial scale by 1980.

The capital cost estimates for commercial size coal dissolution plants directed to producing fuel oil for utility use range from $150-$435/KW and the thermal efficiencies for fuel production from 63-74%. The cost values cannot be considered firm but indicate that the cost will be in excess of low Btu gas generation plants.

Liquid fuels offer a distinct advantage from a storage standpoint. The fuel processing plant can be operated continuously at or near maximum capacity independent of the electric power generating plant. The load-factor turn-down and load following problems associated with low Btu gas plants are nominally eliminated. All potential environmental problems can be handled.

Coal dissolution plants require several processing steps and would be considered complex. Control and operation should not be a problem because of the years of experience in petroleum processing. It is natural to expect that these plants will be operated by petroleum companies and the fuels sold for electric power generation.

As crude oil shortages persist, it is quite likely that coal liquefaction and coal pyrolysis plants will be built for gasoline, fuel oil and chemical feed stocks when scale-up data become available. Heavy residual oils from such plants should fill utility plant needs as they do today.

Recommendations for research development support in coal dissolution and liquefaction are:

<u>Catalytic Coal Liquefaction</u> is worthy of support. Coal liquefaction plants will be operated and the fuel oil products sold to utility plants. Although there are a number of processes being proposed for coal liquefaction, we believe that the H-coal process with ebullated bed reactor is most advanced and thus more likely to reach commercial scale quickly. It is an extension of the H-oil process and the knowledge of that process will facilitate scale-up. Fixed

bed catalytic coal liquefaction has some inherent advantages and should be encouraged.

The Southern Services Wilsonville Pilot Plant operation should be continued and expanded. Support should be forthcoming to carry on such work as:

a) Evaluate congealed liquid product

b) Modify system to operate on synthesis gas to evaluate potential for liquid products (coordinate operations with Tacoma plant to evaluate greater number of coals and operating conditions)

c) Evaluate other solids - extract separation schemes and combinations of schemes

1) Hydroclones

2) Totally submerged filter

A Slurry Pump Loop is needed. Processes which use coal slurries, including liquefaction, have a common need for equipment development. The successful continuous operation of the pumps serving the Black Mesa coal slurry pipeline should be noted. Transfer of the technology to higher temperature coal slurry feed pumps should be almost direct. Pumping oil-coal slurries cold and hot, pressure let-down systems, and possible heat exchange with practical size equipment should be conducted with "live" slurries. Therefore, support is recommended for the development of high temperature slurry pumps and pressure let down methods by equipment manufacturers.

a) Build and operate a test loop to evaluate commercial size pumps, pressure let down equipment and valves. Evaluate performance, measure corrosion and erosion. This might be done at Cresap, West Virginia.

b) Incorporate new developments into the loop for evaluation as they become available.

Insitu Combustion of Coal

The insitu combustion of coal could produce low Btu gas which could be desulfurized for utility power generation. Success to date, both physically and economically has been of such low grade that one cannot foresee successful developments near enough at hand to warrant any large scale projects until the technology is more advanced. Small projects which improve the understanding of the process would seem reasonable. The use of fracturing and explosives to break up the coal bed to permit fluid transmission and uniform combustion may be worthwhile experiments to consider. Study of the nature of the flow channels in coal deposits, and of the gas retention qualities of caprocks both cold and hot are intermediate steps needed. Present work is supported by the Bureau of Mines.

SELECTED BIBLIOGRAPHY
COAL CONVERSION PROCESSES

The following sources are selected for their availability and their coverage of the subject. First, there is a general list of references describing the uses of coal as a clean fuel. Then, references are broken down by subject.

General References

Office of Coal Research, Annual Reports, 1973, 1973, etc.

Lowry, H.H., Chemistry of Coal Utilization, Volumes I & II, John Wiley and Sons, New York, 1945.

Lowry, H.H., Chemistry of Coal Utilization Supplementary, Volume, Wiley and Sons, New York, 1963.

National Academy of Engineering Report, "Evaluation of Coal Gasification Technology, Part 1, Pipeline Quality Gas," COPAC-6, Washington, D.C., 1972.

Hottel, H.C., and J.B. Howard, New Energy Technology, Some Facts and Assessments, MIT Press, Cambridge, Mass., 1971.

Bituminous Coal Research Inc., Gas Generator Research and Development - Survey and Evaluation.

Squires, A.M., "The Fossil Fuel Development Gap," paper at Conference on Energy and the Environment sponsored by NSF, Las Crobas, Puerto Rico, February 22-24, 1972.

Matthews, C.W., "Coal Gasification for Electric Power," Proceedings of the American Power Conference, 1972, Vol. 34.

Clean Fuels from Coal Symposium, Collected Papers, IGT, Chicago, Illinois, Sept. 10-14, 1973.

American Gas Association, Fifth Annual Conference on Pipeline Quality Gas, Chicago, October 1973.

Energy Technologies for the Future, Summary of Conference at Saxton River, Vermont, July 1972, Engineering Foundation, N.Y.

Coal Cleaning

Program for Processes for the Selective Chemical Extraction of Organic and Pyritic Sulfur from Fossil Fuels, Contract EHSD 71-7. Volumes I and II, J.W. Hamersma, E.P. Kontsonkos, M.L. Kraft, R.A. Meyers, G.J. Ogle, L.J. Van Nice, TRW Systems Group, 15 January, 1973.

Froth Flotation Process, Wall Street Journal and New York Times, December 1973.

Chemical Comminution of Coal, Robert Aldrich, Life and Material Sciences Center, Syracuse University.

Liquefaction Processes - General

Consolidation Coal Company, "Summary Report on Project Gasoline", Office of Coal Research, Research and Development Report No. 39, Volume 1.

Kloepper, D.L., et al., "Solvent Processing of Coal to Produce a De-Ashed Product", Office of Coal Research and Development Report No. 9, Contract No. 14-01-001-275 (August 22, 1962 - February 22, 1965).

McIlvried, H.G., S.W. Chuon and D.C. Chronauer, "The Gulf Catalytic Coal Liquids Process", Process Research Division, Report No. 6214RDO15 May 25, 1973, Gulf Research and Development Co.

Akhtar, Sayeed, et al., "Process for Hydrodesulfurization of Coal in a Turbulent - Flow Fixed-Bed Reactor", 71st National Meeting, AIChE, Dallas, Texas, February 20, 1972.

Johnson, C.A., et al., "Product Status of the H-Coal Process," Paper presented at the Clean Fuel from Coal Symposium, IGT, Chicago, Ill., Sept. 10-14, 1973.

Gasification, General

Elliott, Martin A., and Henry R. Linden, "Gas, Manufactured," Chapter in Encyclopedia of Chemical Technology, Vol. 10, pages 353-442, 1966, Second Edition.

Symposium on Coal Gasification etc., Chemical Engineering Progress, 69, No. 3, 31-66 (1973).

Conn, A.L., "Low Btu Gas for Power Plants," CEP, 69, No. 12, 56-61 (1973).

Evaluation of Coal Gasification Technology, Part I, Pipeline-Quality Gas, National Academy of Engineering, Washington, D.C., 1972.

Westinghouse, Industry Team: Westinghouse Electric Corporation, Public Service Indiana; Bechtel Corporation, AMAX Coal Company, Advanced Coal Gasification System for Electric Power Generation, Proposal to Office of Coal Research, United States Department of the Interior, Washington, D.C., April 1972.

Gasification, Specific Process

Bi-gas:

Glenn, R.A. and R.J. Grace, "An Internally-fired Process Development Unit for Gasification of Coal Under Conditions Simulating Stage 2 of the BCR Two-Stage Super-Pressure Process," Am. Gas Assoc., Synthetic Pipeline Gas Symposium, Pittsburg, Pa., 1968.

Grace, R.J., "Development of the Bi-Gas Process", paper presented at the "Clean Fuels from Coal" Symposium,Inst. Gas Tech., Chicago, Ill., Sept. 10-14, 1973.

C.E. Atmospheric Pressure Gasifier:

A Design Study of Atmospheric Pressure Coal Gasification for Electric Power Generation, J.J. Blaskowski and R.W. Koucky, Task II Report, Project 900120, Combustion Engineering Inc., April 9, 1973.

Molten Salt Coal Gasifiers:

Cover, A.E. and W.C. Schreiner and G.T. Skaperdas, Kellogg Coal Gasification Process, CEP, March 1973.

Cover, A.E., W.C. Schreiner and G.T. Skaperdas, "Kellogg's Coal Gasification Process," paper presented at IGT "Clean Fuels from Coal" Symposium, Chicago, Ill., Sept. 11, 1973.

Atomics International Division, Rockwell International Presentation to EPRI, "Molten Salt Gasification of Coal for the Production of Low Btu Fuel Gas", AI-BD-73-20, Chicago, Ill., July 25, 1973.

Stirred Bed Gasifier:

Lewis, P.S., Liberatore, A.J., and McGee, J.P., Strongly Caking Coal Gasified in a Stirred-Bed Producer. BuMines Rept. of Inv. 7644, 1972, 11 pp.

Foster Wheeler Pressurized Gasifier:

Coal Gasification Combined Cycle Pilot Plant, Phase I Draft Report for Office of Coal Research, Foster Wheeler Corporation, August 9, 1973.

Koppers-Totzek:

Farnsworth, J.F., H.F. Leonard, D.M. Mitsak, and R. Wintrell, "Gasification Production of Coal by the Koppers-Totzek Process," paper presented at the "Clean Fuels from Coal Symposium," Inst. Gas Tech., Sept. 10-14, 1973.

Dressler, R.G., et al., "Operation of a Powdered-Coal Gasifier at Louisiana, Mo.", U.S. Bureau of Mines Report of Investigations 5038, April 1954.

Winkler:

Banchik, I.N., "The Winkler Process for the Production of Low Btu Gas from Coal," Clean Fuels from Coal Symposium, IGT, Chicago, Ill., Sept. 10-14, 1973.

Synthane:

Forney, A.J. and McGee, J.P., "The Synthane Process - Research Results and Prototype Plant Design," Presented at the Fourth AGA Synthetic Pipeline Gas Symposium, Chicago, Ill., Oct. 30-31, 1972, 1t pp.

Feldman, H.F., et al., Supplemental Pipeline Gas from Coal by the Hydrane Process, Presented at the 71st National Meeting, AIChE, Dallas, Texas, February 20-23, 1972.

Agglomerating Ash Coal Gasifier:

Goldberger, W.M., "The Union Carbide Coal Gasification Process", Presented at Fourth Synthetic Pipeline Gas Symposium, Chicago, Oct. 30-31, 1972.

Goldberger, W.M. , "Fly-Ash Emission and Erosion by Fly-Ash from a Self-Agglomerating Fluidized Bed Coal Burner", AIChE Meeting, Detroit, June 1973.

Corder, W.C., and H.R. Batchelder and W.M. Goldberger, Union Carbide/Battelle Coal Gasification PDV Design, Fifth Synthetic Pipeline Gas Symposium, Chicago, October 1973.

Lurgi:

Elgin, D.C. and H.R. Perks, Trials of American Coals in Lurgi Pressure-Gasification Plant in Westfield, Scotland, Fifth Synthetic Pipeline Gas Symposium, Chicago, October 1973.

Rudolph, P.F., New Fossil Fuel Power Plant Process Based on Lurgi Pressure Gasification of Coal, Lurgi Gesellschaft fur Warne-und-Chemotechnik MBH, April, 1970.

Hygas:

Schora, F.C., B.S. Lee and J. Huebler, "The Hygas Process," presented at the 12th World Gas Conference, Nice, 1973.

Lee, B.S., "Status of Hygas Process - Operating Results, presented at the Fifth Synthetic Pipeline Gas Symposium, Chicago, October 1973.

CO_2 Acceptor Process:

Fink, Carl, "The CO_2 Acceptor Process," paper presented at the "Clean Fuels from Coal" Symposium, Inst. Gas Tech., Chicago, Ill., Sept. 10-14, 1973.

Insitu Combustion of Coal

A Current Appraisal of Underground Coal Gasification, Report USBM C-73671 (December 1971) by A.D. Little.

Schrider, L.A. and J. Pasini, III,"Underground Gasification of Coal, Pilot Test", Hanna, Wyoming, October 1973. Paper at AGA Conference, O'Hare Inn.

Fluidized Combustion

D.H. Archer, et al., Evaluation of the Fluidized Bed Combustion Process. Westinghouse NTIS PB 211 494, Nov. 15, 1971.

A.H. Bagnulo, et al., Development of Coal Fired Fluidized Bed Boilers, Volume I (1970). Pope, Evans and Robbins for OCR Contract 14-01-0001-478.

J.W. Bishop, et al., Development of Coal Fired Fluidized Boilers. Pope, Evans and Robbins for OCR, Volume II, Supt. Doc. 2414 0048, February 1972.

H.R. Vogel, et al., Reduction of Atmospheric Pollution by Application of Fluidized Bed Combustion, Argonne National Laboratory ANL/ES-CEN 1005, EPA R-2-73-253 (1972).

H.R. Hoy and A.G. Roberts, Fluidized Combustion of Coal at High Pressures, AIChE Symposium Series, Vol. 68, No. 126 (1972).

Esso Engr. EPA Studies. NTIS PB 210-246, Dec. 3, 1971.

Shopp, A. et al., Studies of the Fluidized Lime-Bed Coal Combustion Desulfurization System. Report Control Systems Division, Office of Air Programs, Environmental Protection Agency, Dec. 31, 1971.

Hammons, G. and A. Shopp, A Regenerative Limestone Process for Fluidized Bed Coal Combustion and Desulfurization, Prepared for Process Control Engineering Program, Air Pollution Control Office, EPA. Feb. 28, 1971.

"The Scale-up of a Fluidized-Bed Combustion System Utility Boilers", Godel, Albert and Paul Cosan, CEP Symposium Series 67, No. 116, 210 (1971).

"Air Pollution Control Through New Combustion Process", Ehrlich, Shelton, Combustion, August 1971, p. 36.

"ER&E Sets Pilot Plants to Burn High Sulfur Coal with Low SO_2 Discharge," Oil and Gas J, Nov. 20, 1972, p. 83.

"Fluidized Combustion of Coal at High Pressures," Hay, H.R. and A.G. Roberts, CEP Symposium Series 68, No. 126, 225 (1972).

Pyrolysis and Base Coal Refinery

COED:

A.H. Strom and R.I. Eddinger, COED Plant for Coal Conversion, Chem. Eng. Prog., Vol. 67, No. 3, p. 75 (1971).

J.F. Jones, Project COED, IGT Symposium, Sept. 10-14, 1973.

J.F. Jones, *et al.*, Char Oil Energy Development, FMC Corporation to OCR, R&D Report No. 73, July '71-June '72.

Toscoal:

Carlson, F.B., L.H. Yardumian and M.T. Atwood, "The Toscoal Process for Low Temperature Pyrolysis of Coal", Chem. Eng. Prog. 68, No. 3, 50 (1973).

Atwood, M.T., Toscoal Process, Presented at the Clean Fuels from Coal Symposium, IGT, Chicago, Ill., Sept. 10-14, 1973.

Garrett:

Adam, D.E., S. Sach and A. Sass, "The Garrett Pyrolysis Process", paper presented at 66th Annual Meeting AIChE, Philadelphia, Pa., Nov. 15, 1973.

McMath, R.E. Lumpkin, and A. Sass, "Production of Gas from Western Sub-bituminous Coals by the Garrett Flash Pyrolysis Process", paper presented at 66th Annual AIChE Meeting, Philadelphia, Pa., Nov. 15, 1973.

Stack Gas Cleaning

Falkenberry, H.L. and Alex Weir, Jr., Status Report and Recommendations on Control of Gaseous Emissions to Task Force on Utilization of Coal of EPRI (1973).

Final Report Sulfur Oxide Control Technology Assessment Panel (SOCTAP) on Projected Utilization of Stack Gas Cleaning Systems by Steam-Electric Plants, April 15, 1973.

M. Ross et al., Energy Costs of Limiting the Degradation of the Environment - Report to Ford Foundation's Sponsored Energy Policy Project, Physics Department, University of Michigan, June 26, 1973.

Conser, R.E. and R.F. Anderson, "New Tool Combats SO_2 Emissions", Oil and Gas J., October 29, 1973, p. 81-86.

Limestone for Stack Gas Treatment

Limestone and Dolomite, Harold A. Hubbard and George E. Ericksen, U.S. Geological Survey Professional Paper 820, 1973.

Availability of Limestone and Dolomite, M.W. Kellogg, Co., 1972, Final Report, EPA Contract CPA 70-68.

Properties of Calcium and Magnesium Carbonates, D.L. Graf and J.E. Lamar, Economic Geology, pages 639-713, Fiftieth Anniversary Volume, Alan Bateman, Ed., Lancaster Press, 1955.

Tall Stacks

A. Grennard and F. Ross, Progress Report on Sulfur Dioxide, Combustion, Vol. 45, No. 7, p. 4, January 1974.

AUGUST 24, 1973

THE UNIVERSITY OF MICHIGAN NEWS RELEASE

CONTACT: JIM ALLYN

ANN ARBOR---A team of University of Michigan engineers has undertaken an intensive, seven-month study to determine which of the existing methods for converting coal to clean fuels are the most likely to prove commercially feasible in the near future.

"The Board of Directors of the Electric Power Research Institute (EPRI) has approved a budget of $150,000 and contract negotiations are in progress," said project coordinator Donald L. Katz, the Alfred Holmes White University Professor of Chemical Engineering at U-M.

"Our goal is to recommend to EPRI those processes whose development warrants acceleration through the Institute's support," Prof. Katz said. EPRI is a national effort by the electric power industry, both public and private, to sponsor energy research of common interest and importance.

Joining Katz in the project are Dale E. Briggs, John E. Powers and M. Rasin Tek, professors of chemical engineering; Brymer Williams, professor of chemical and metallurgical engineering; Edward R. Lady, professor of mechanical engineering, all at U-M. Walter E. Lobo, independent consulting engineer, will be project consultant.

"Over the next few decades, clean fuels derived from coal will play a key role in helping electric utility companies handle the ever increasing demand for energy," Katz explained, adding that "clean" coal is that which has had most of the sulfur, a serious pollutant, removed.

"However, coal can be converted to clean fuels by either gasification, liquefication, or solvent extraction," he continued, "and there are currently ten major coal gasification processes and several for liquefication and solvent extraction."

(more)

In view of the steadily mounting energy crisis, the U-M chemical ngineer pointed out, EPRI cannot afford either the time or the money equired to see that every coal conversion process be fully explored.

"By analyzing and comparing the different processes, we hope to assist PRI in focusing and intensifying its research so that the best processes an be realized in time to help alleviate the energy dilemma," Katz mphasized.

He said that all conversion processes which satisfy the environmental tandards established by the Environmental Protection Agency will be onsidered. He said a comprehensive method for evaluating the different rocesses will be developed by the U-M team.

"We will be interested in such things as the percentage of energy emaining after cleaning, the difficulty in the physical handling of the uel, the simplicity of the equipment required, the type of waste left after leaning and problems associated with its disposal, the overall economics, nd other factors," he observed.

Initially, the group will examine reports describing the processes and eview papers on the subject prepared by the EPRI Task Force of Utilization f Coal. But it also plans to conduct extensive interviews with engineers nd those managing the organizations sponsoring or offering coal conversion rocesses to the industry.

"The engineers on the project have considerable experience in industry," atz noted, "and when it comes to handling thermodynamics, rate processes, r other technical aspects of these various processes, they will be fully apable of putting the information gathered into proper perspective." The inal report prepared by the group for EPRI will be presented in January 1974.

Commenting on the project, David V. Ragone, dean of the U-M College of ngineering, said, "Nuclear power is not yet ready to assume the major ortion of power production. And shortages of natural gas and limited omestic crude oil supply have put a new emphasis on coal. Therefore, I m highly pleased that our engineers are participating in a project that ltimately could help our country meet its energy needs through the nvironmentally sound consumption of coal."

# # # # # #

Katz;Ragone;Eng;Ind)(R1,2;D1;EW;B1;Engl,4;Ecol;SG1) 100 sp. bjw

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Technical Information Service
Springfield, VA 22161 (703) 605-6000