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ASSESSMENT OF UNDERGROUND COAL GASIFICATION IN BITUMINOUS COALS

Final Report, Executive Summary

January 1982

Work Performed Under Contract No. AC21-80MC14584

Williams Brothers Engineering Company
Process Division
Resource Sciences Center
Tulsa, Oklahoma

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FINAL REPORT
EXECUTIVE SUMMARY

VOLUME I OF IV

ASSESSMENT OF UNDERGROUND COAL GASIFICATION IN BITUMINOUS COALS

prepared for the
U.S. DEPARTMENT OF ENERGY
MORGANTOWN ENERGY TECHNOLOGY CENTER
UNDER CONTRACT NO. DE-AC05-80MC 14584

PROCESS DIVISION
OF
WILLIAMS BROTHERS ENGINEERING COMPANY

RESOURCE SCIENCES CENTER • TULSA, OKLAHOMA 74177

ACKNOWLEDGEMENT

The Williams Brothers Engineering Company wishes to express its appreciation to J. W. Martin and R. S. Grumbach, both of the U.S. Department of Energy, and Dr. Richard Mungen, consultant, for their assistance and guidance during the development of the Assessment of Underground Coal Gasification in Bituminous Coals.

ABSTRACT

This report describes the bituminous coal resources of the United States, identifies those resources which are potentially amenable to Underground Coal Gasification (UCG), identifies products and markets in the vicinity of selected target areas, identifies UCG concepts, describes the state of the art of UCG in bituminous coal, and presents three R & D programs for development of the technology to the point of commercial viability. Of the 670 billion tons of bituminous coal remaining in-place as identified by the National Coal Data System, 32.2 billion tons or 4.8% of the total are potentially amenable to UCG technology. The identified amenable resource was located in ten states: Alabama, Colorado, Illinois, Kentucky, New Mexico, Ohio, Oklahoma, Utah, Virginia, and West Virginia. The principal criteria which eliminated 87.3% of the resource was the minimum thickness (42 inches).

Steeply dipping (>30°) bituminous coal beds in the Eastern United States are very poorly defined due to the lack of value of the resource to mining. Two steeply dipping coal bed areas were identified as potentially containing the minimum resource (3.5 million tons) considered feasible for a commercial operation: Coosa Field of Alabama and the Chestnut Ridge area of Pennsylvania.

The North-East-Central United States was identified as having the potentially greatest market for products of UCG. Power generation using gas turbines in either the cogeneration or combined cycle mode was determined to be the best use of low or medium BTU gas.

As a result of recent advances in directional drilling control technology and the likelihood of even more improvement in the near term, the Open Borehole concept was chosen to have the

highest potential for successful application of UCG in bituminous coals. Costs of using the Open Borehole concept compare favorably with other concepts evaluated at similar depths and coal seam thicknesses.

Three R & D programs were developed using three different concepts at two different sites. Open Borehole, Hydraulic Fracture, and Electrolinking concepts were developed. The total program costs for each concept were not significantly different. In the Open Borehole concept lab and modeling work was estimated to be $273,000; economic feasibility study, $415,000; bench scale tests, $435,000; and initial field tests, $20.7 million. A total program cost of $22.0 million was determined.

The study concludes that much of the historical information based on UCG in bituminous coals is not usable due to the poor siting of the early field tests and a lack of adequate diagnostic equipment. This information gap requires that much of the early work be redone in view of the much improved understanding of the role of geology and hydrology in the process and the recent development of analytical tools and methods.

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1.0 INTRODUCTION

The Assessment of Underground Gasification of Bituminous Coals was performed for the Morgantown Energy Technology Center of the Department of Energy by the Williams Brothers Engineering Company of Tulsa, Oklahoma.

The term of the contract lasted from July 21, 1980 to January 31, 1982.

The contract Statement of Work specified that Williams Brothers was to conduct a study to result in a detailed outline of a program, including estimated costs, to develop one to three concepts for the recovery of energy from bituminous coal by in situ gasification at a site, or sites, having accessible coal located within regions near or containing major end use markets.

The contract specified three major technical phases:

PHASE I - Catalog the Bituminous Coal Resources

PHASE II - Identify, Evaluate, and Rank Concepts

PHASE III - Formulate an R & D Program

The Final Report is composed of four volumes. Volume II was issued as four separate books.

The breakdown is as follows:

Executive Summary	- Volume I
Phase I	- Volume II
Phase II	- Volume III
Phase III	- Volume IV

A change of scope to include cataloging of the eastern bituminous coal seams with a dip greater than 30 degrees was made during execution of the contract.

The concept evaluation stresses concepts which have been demonstrated rather than more complex processes which have been hypothesized and, as such, have a lower probability of success. A high percentage of the significant field, laboratory, and modeling effort to-date is identified.

Williams Brothers Engineering Company has been continuously active in the development of underground coal gasification technology since 1972. The work presented in this study is based primarily on Williams Brothers' experience and background in UCG. Williams Brothers possesses one of the most complete UCG reference literature resources. In addition, extensive use was made of Soviet translations and basic data/information generated in the U.S. by the Lawrence Livermore National Laboratory. Research conducted and/or funded by the Bureau of Mines, the Morgantown Technology Center of the Department of Energy, and the National Coal Board of Great Britain were extensively referred to.

2.1 BITUMINOUS COAL RESOURCE EVALUATION - PHASE I REPORT

2.1.1 INTRODUCTION

The Phase I report - Assessment of Underground Coal Gasification in Bituminous Coals includes the following major sections:

Sections 1.0-3.0 contain general coal resource information and criteria for resource evaluation.

Section 4.0 contains a catalog description of the identified bituminous coal resources in the twenty-three states (twenty-eight states are listed in the NCRDS files) which contain 99+% of the bituminous coal reserves.

Section 5.0 contains a catalog description of the identified bituminous coal resources "amenable" to UCG technology. For a coal bed to be "amenable" to UCG the coal bed itself, the surrounding structural geology, and the surface environment had to pass established evaluation criteria. Coal resources in ten states were described.

Section 6.0 contains a catalog description of the identified bituminous coal resources contained within coal seams having a dip greater than 30 degrees. Nine states were identified as having such resources.

Section 7.0 contains an identification and preliminary list of potential UCG sites. Four states were reviewed.

Section 8.0 contains a review of products which can be derived from the underground gasification of amenable seams and a survey of potential markets.

Appendix A contains a catalog of the ECOAL, WCOAL, and BMALYT data files from the National Coal Resources Data System (NCRDS), listing information pertaining to the total "identified bituminous coal resources" in the contiquous United States. An "identified bituminous resource" is classified as the total quantity of coal in the ground within beds of at least 14 inches thickness as determined by actual physical measurements, not just inferred based on limited data. Maximum overburden thickness is limited to 6,000 feet.

Appendix B contains county maps for ten states identified as having UCG amenable bituminous resources. Tonnage estimates of total bituminous coal resource in seams ≥42 inches in thickness are listed by seam in the counties of occurrence. Total coal amenable to UCG in the same seams is then listed.

The Phase I report (Volume II) is composed of four books. Sections 1.0 - 7.0 are in Book 1 of 4. Section 8.0 is in Book 2 of 4. Appendices A and B are in Books 3 of 4 and 4 of 4, respectively.

2.1.2 OBJECTIVES

The objectives of the Phase I Report - Assessment of Underground Coal Gasification in Bituminous Coals include:

1. Identify and catalog the bituminous coal resources amenable to UCG in the contiguous United States.

2. Identify and catalog bituminous coal seams in the eastern United States having dips greater than 30 degrees.

3. Identify a preliminary list of sites suitable for future UCG development.

4. Review and identify marketing opportunities in the vicinity of selected sites.

2.1.3 DATA BASE

The primary source of coal data in the United States is contained in the National Coal Resources Data System (NCRDS). This system contains information on "identified coal resources" of the United States as gathered by the United States Geological Survey. It also contains representative chemical analyses of coal seams as reported by the United States Bureau of Mines.

The NCRDS is composed of the ECOAL, WCOAL, and BMALYT files. The ECOAL file contains resource estimates and information for states east of the Mississippi River and provides information on the county of occurrence, name of the coal field, geologic ages, formation name, coal rank, seam thickness, thickness of overburden, and reliability of data. Also noted is whether the tonnage estimate is for original coal in the ground or for the amount remaining as of the date of the publication.

The WCOAL file is exactly the same as the ECOAL file except that it records the information for coal-bearing states west of the Mississippi River. The age of the information in both of these files varies from turn-of-the-century statistics to information based on the most recent drilling data.

The U.S. Bureau of Mines chemical analysis (BMALYT) file is a computer accumulation of standard chemical analyses on tipple, delivered, and channel coal samples throughout the United States. The data includes proximate and/or ultimate analyses, BTU value, ash softening temperature, free swelling index, and Hargrove grindability index. The analyses are located by state, county, bed code and name, mine, and nearest town code. Rank is calculated by the ASTM formula.

Appendix A of the Phase I report contains those portions of the ECOAL, WCOAL, and BMALYT files of the NCRDS which pertain to bituminous coals in the lower forty-eight states of the United States. Because of the wide variation in the BMALYT information available for individual coal seams, a printout of averages for each seam was included in Appendix A.

Besides the NCRDS files, other information depositories utilized included those of the U.S. Geological Survey libraries at several locations, U.S. Bureau of Mines libraries and files, and public documents published by these two Federal agencies. For specific information about potential sites, it was necessary to visit several state geological surveys and research their open files. Numerous states and private corporations were also contacted in an effort to secure their support and assistance in the acquisition of the latest data available.

2.1.4 UCG AMENABLE BITUMINOUS RESERVES WITH DIP LESS THAN 30 DEGREES

A. EXPLORATION PROCEDURE

Review of the NCRDS files pertaining to "identified bituminous coals" revealed a total of twenty-eight bituminous coal bearing states. The August 1980 NCRDS estimate of the total "identified" bituminous coal reserves contained in these states, except Montana and Kansas for which estimates were not available, was 690 billion short tons.

Alaska was eliminated from the list of bituminous coal bearing states since it is not one of the lower forty-eight contiguous states. This left the total estimated reserve of identified bituminous coal at 670 billion short tons.

Of the remaining twenty-seven states, Georgia, Idaho, Michigan, and North Carolina were eliminated because they contain only limited reserves of bituminous coal. A limited reserve was defined as 250 million tons, less than 0.04% of the total estimated reserve of 690 billion tons. The above four states contain a combined total of only 361 million tons, 0.05% of the total estimated resource.

The remaining twenty-three states were reviewed in detail and a descriptive catalog of the major coal field in each state was prepared. Coal resource maps, lithological sequence drawings, stratigraphic correlation charts, stratigraphic column drawings, and coal physical and chemical analyses tables were prepared for most of the states. In states where oil and gas production is significant, a descriptive section on oil and gas production was included. Other items discussed include folding and faulting and roof and floor conditions.

Having examined the above twenty-three states, which contain 99+% of the identified bituminous reserves, a descriptive catalog of the UCG amenable reserves of bituminous coal was prepared.

To develop the catalog of UCG amenable reserves, four stages of review were used. Criteria pertaining to "site" and "resource" were applied at each stage of review, resulting in the elimination of various counties and states.

Due to the subjective nature of some of the criteria set forth in Table 2.1-1, the following analysis may not contain all potentially amenable coal resources.

The four stages of review are summarized in Table 2.1-1.

B. <u>RESULTS</u>

1. DATA BASE

Appendix A is the computer listing of the NCRDS data for the identified bituminous coal deposits in the twenty-eight coal-bearing states except Alaska.

Although estimates of the bituminous reserves are available based on drilling and geologic evidence, the estimates are still only approximate. The margin of error can be up to plus-or-minus forty to fifty percent. Continued coal resource evaluations by government and industry will continue to improve these estimates.

Table 2.1-2 lists the twenty-eight bituminous coal-bearing states. NCRDS tonnage estimates for each state are given.

TABLE 2.1-1

EXPLORATION PROCEDURE USED TO
IDENTIFY UCG AMENABLE BITUMINOUS RESERVES

STAGE	ACTIVITY	STATES ELIMINATED
I	1. Eliminate states having less than 2 billion tons of identified reserves.	Arkansas, Maryland, Tennessee, Washington
	2. Eliminate states reporting only "inferred" bituminous reserves or had no data in the NCRDS.	Kansas, Missouri, Texas
	3. Review remaining coal-bearing states for amenability to UCG on a county and seam basis using the following criteria:	
	a. Seam thickness $\geq$42 inches.	
	b. 3.5 million tons per 42 inch seam available.	
	c. Minimum overburden thickness of 300 feet.	
II	1. Eliminate seams described as highly variable in thickness over short distances.	Arizona, Indiana, Wyoming
	2. Eliminate seams containing multiple partings	
	3. Eliminate seams with less than 50 feet of interburden between the target seam and an overlying coal seam greater than 24 inches thick.	
III	1. Eliminate resources based on the following buffer zone criteria between existing land uses and potentially amenable sites:	Iowa, Missouri Pennsylvania
	a. Oil and gas fields - one mile.	
	b. Populated areas (minimum population = 100 residents)-one mile.	
	c. Federal, state, and county numbered highways - one-quarter mile on either side.	
	d. Railroad lines - one-quarter mile on either side.	
	e. Rivers and lakes - one mile.	
	f. Active underground mines - two miles.	
	g. Abandoned underground mines - one mile.	
IV	Review state geological survey data, drilling logs, and mining maps to further identify UCG amenable reserves.	

TABLE 2.1-2

EVALUATION OF UCG AMENABLE BITUMINOUS RESERVES

(Figures Are NCRDS Estimates of Total Identified Bituminous Coal Reserves per State in Millions of Short Tons.)

NO.	STATES LISTED IN NCRDS AS CONTAINING BITUMINOUS COAL RESERVES	ESTIMATED TOTAL BITUMINOUS RESERVES	STATES ELIMINATED BY GIVEN CRITERIA				STATES REMAINING AFTER REVIEW	COAL REMAINING ≥ 42" THICK	COAL AMENABLE TO UCG
			LESS THAN 2 BILLION TONS	INFERRED DATA	LITHOLOGY	BUFFER ZONES			
1	Alabama	13,753					13,753	707	707
2	Alaska	19,429	(a) 19,429						
3	Arizona	4,348			4,348				
4	Arkansas	1,815	1,815						
5	Colorado	63,258					63,258	22,208	14,884
6	Georgia	23	23						
7	Idaho	9	9						
8	Illinois	137,330					137,330	38,243	9,134
9	Indiana	37,293			37,293				
10	Iowa	7,236				7,236			
11	Kansas	(b)							
12	Kentucky	74,430					74,430	14,270	1,645
13	Maryland	859	859						
14	Michigan	219	219						
15	Missouri	31,667				31,667			
16	Montana	(b)							
17	New Mexico	10,948					10,948	2,459	2,299
18	North Carolina	110	110						
19	Ohio	46,274					46,274	1,716	82
20	Oklahoma	7,207					7,207	1,656	257
21	Pennsylvania	71,008				71,008			
22	Tennessee	1,884	1,884						
23	Texas	8,976		8,976					
24	Utah	25,885					25,885	4,079	2,941
25	Virginia	10,774					10,774	478	140
26	Washington	1,868	1,868						
27	West Virginia	100,299					100,299	1,403	125
28	Wyoming	13,234			13,234				
	TOTALS	690,136	26,216	8,976	54,875	109,911	490,158	85,219	32,214
	STATES ELIMINATED	199,978							
		490,158							

(a) Eliminated by not being one of the 48 contiguous states .

(b) NCRDS data not available. These states were eliminated based on other data.

The twenty-three states remaining after eliminating Alaska and states having less than 250 million tons of bituminous coal were examined in detail and resource descriptions prepared. These descriptions appear in Section 4.0 and form a major portion of the Phase I report.

Section 4.0 combined with Appendix A forms a complete catalog description of the major bituminous coal bearing states in the contiguous United States.

2. CATALOG OF UCG AMENABLE BITUMINOUS COAL

Application of the first stage evaluation criteria (see Table 2.1-2) requiring a total state tonnage of >2 billion tons resulted in the elimination of eight states. Alaska had been eliminated, not being one of the contiguous states. These nine states contain a total of 26,216 million tons, 3.8% of the total estimated bituminous reserves of 690 billion tons. The remaining nineteen states contain 96.2% of the total bituminous reserves located in 371 counties.

Texas was eliminated based on the fact much of the reported bituminous coal is only inferred to exist. Kansas and Montana were eliminated based on a lack of data.

Application of the second stage of resource evaluation pertaining to lithology resulted in the elimination of an additional three states - Arizona, Indiana, and Wyoming. This eliminated a total of 54,875 million tons of bituminous coal, 8.0% of the estimated total bituminous reserves. The remaining thirteen states contain a total of 600 billion tons, 154 million tons of which are potentially UCG amenable bituminous coal, approximately 23% of the total reserve base.

The stage three evaluation on the remaining thirteen states resulted in the elimination of an additional three states - Iowa, Missouri, and Pennyslvania and 50 counties, leaving ten states and 125 counties. The eliminated states contain large reserves of bituminous coal totaling 109,911 million tons 15.9% of the original total. The remaining ten states, contain 490,158 million tons of bituminous reserves, 85,219 million tons of which are believed to exist in seams ≥42 inches thick and 32,214 million tons of which may be potentially amenable to UCG.

Stage four involved a detailed review of the remaining ten states and 125 counties. Review of drilling logs and mining maps eliminated additional counties from consideration. This detailed review of data permitted delineation of reserves with 300 to 500 feet of overburden and resources with greater than 500 feet of cover for most states.

County maps of UCG amenable resources for ten states, except for Colorado which lacks sufficient resource data, were prepared. The resource estimates, where seam data were available, were developed by estimating the area in each county underlain by amenable resources and multiplying this area by the average seam thickness. For a given county, if a site met all the established evaluation criteria and was underlain by more than one amenable seam, tonnage estimates were developed for each seam individually.

Section 5.0 of the Phase I report presents a description of the total bituminous resources, an estimate of the total bituminous tonnage in seams ≥42 inches thick, and an estimate of how much of the bituminous coal in seams ≥42 inches thick is amenable to UCG based on the established evaluation criteria.

Appendix B presents county maps for the ten states identified in the evaluation process showing specific areas underlain with potential UCG amenable bituminous coal reserves.

Summary tables in Appendix B for each state indicate on a county-by-county and seam-by-seam basis the following items:

1. Total coal resources in seams ≥42 inches thick.
2. Total coal amenable to UCG.
3. UCG coal beneath federal lands.
4. UCG coal beneath private lands.
5. UCG coal beneath tribal lands.
6. Coal amenable to UCG under 300 to 500 feet of overburden.
7. Coal amenable to UCG under greater than 500 feet of overburden.

Table 2.1-3 is an example of a partial summary for the state of Illinois. As an example, Figure 2.1-1 shows the UCG amenable areas for Hamilton County, Illinois, which contains the target areas IL-4 and IL-5 which will be described later.

Table 2.1-4 is an overall summary of the UCG amenable bituminous coal in the ten states reviewed. Figure 2.1-2 presents these results graphically. The impact of the ≥42 inch seam thickness criteria appears as a reduction of amenable reserves from 71% to 12.4% of the total base of 690 billion tons. The impact of other evaluation criteria is represented by additional decreases (except for Alabama) in UCG amenable coal. The final result of the evaluation was an estimate of 32,214 million tons of UCG amenable coal, 4.8% of the total reserve.

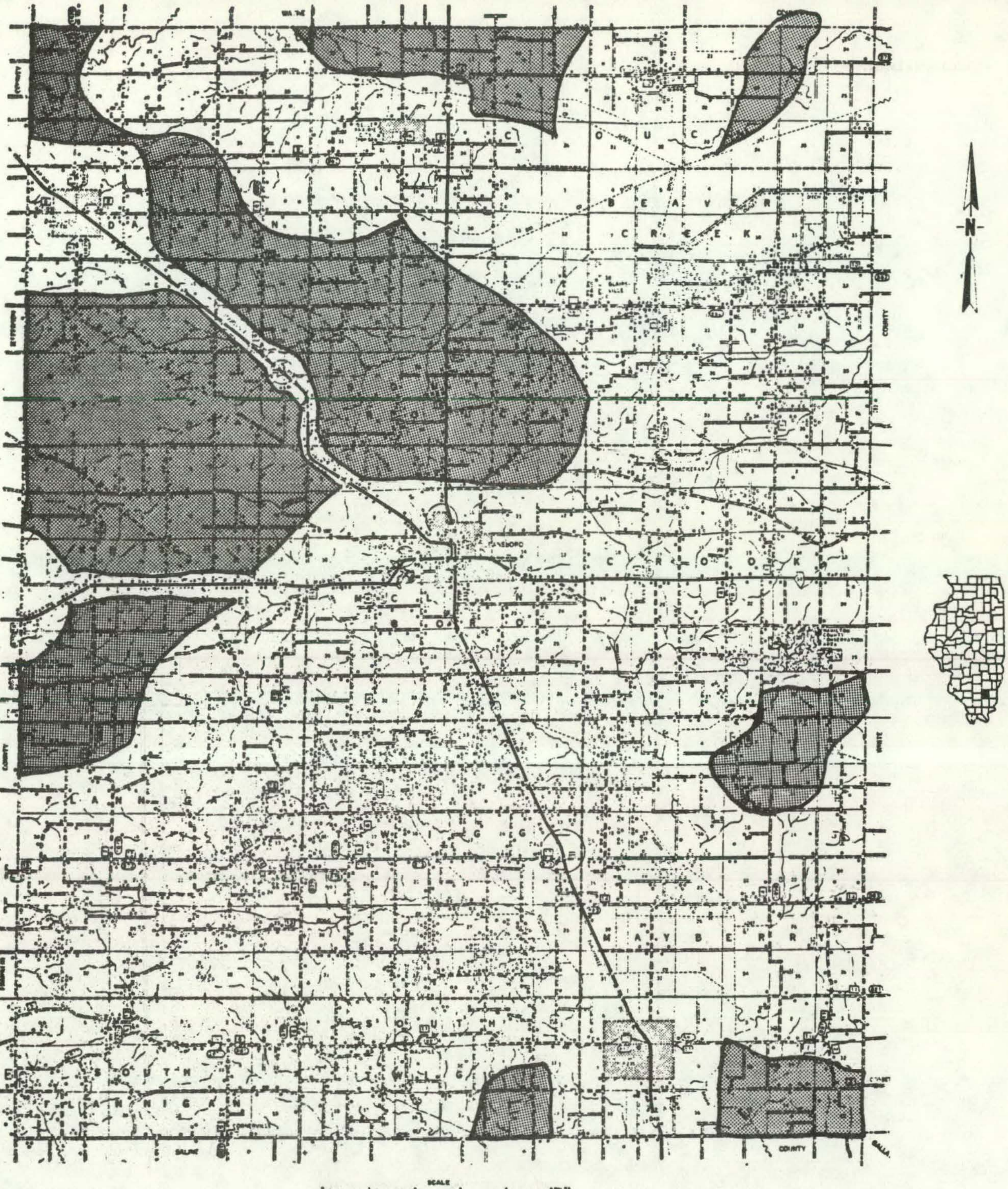
TABLE 2.1-3

UCG DATA SHEET

STATE OF ILLINOIS

(ALL FIGURES IN MILLIONS OF TONS)

COUNTY/SEAMS	TOTAL COAL RESOURCE ≥ 42" IN THICKNESS	TOTAL COAL AMENABLE TO UCG	UCG COAL BENEATH FEDERAL LANDS	UCG COAL BENEATH STATE LANDS	UCG COAL BENEATH TRIBAL LANDS	COAL AMENABLE TO UCG UNDER 300-500' OF OVERBURDEN	COAL AMENABLE TO UCG UNDER GREATER THAN 500' OF OVERBURDEN	COMMENTS
CLARK COUNTY								
NO. 7 SEAM	94.9	94.9*				94.9		
CLAY COUNTY								
NO. 6 SEAM	190.9	121.1					121.1	
CRAWFORD COUNTY								
NO. 6 SEAM	297.1	172.2				172.2		
NO. 5 SEAM	219.5	140.0					140.0	
INDIANA NO. 3 SEAM	452.4	124.2					124.2	
EDGAR COUNTY								
INDIANA NO. 3 SEAM	864.4	401.4					401.4	
FRANKLIN COUNTY								
NO. 6 SEAM	2016.1	171.5					171.5	
NO. 5 SEAM	1757.9	128.6					128.6	
GALLATIN COUNTY								
NO. 6 SEAM	1093.6	45.7				45.7		
NO. 5 SEAM	1301.5	38.1				38.1		
HAMILTON COUNTY								
NO. 6 SEAM	2612.0	607.7					607.7	
NO. 5 SEAM	1930.9	347.5					347.5	
JEFFERSON COUNTY								
NO. 6 SEAM	2641.3	588.1					588.1	
NO. 5 SEAM	550.2	120.8					120.8	



SEAM NO.'S 5 & 6

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HAMILTON CO., ILL.

Date October 1, 1981

Approved *R. G. Beeson*

FIGURE

2.1.4-8a

DES-F-A1000

TABLE 2.1-4

UCG DATA SHEET

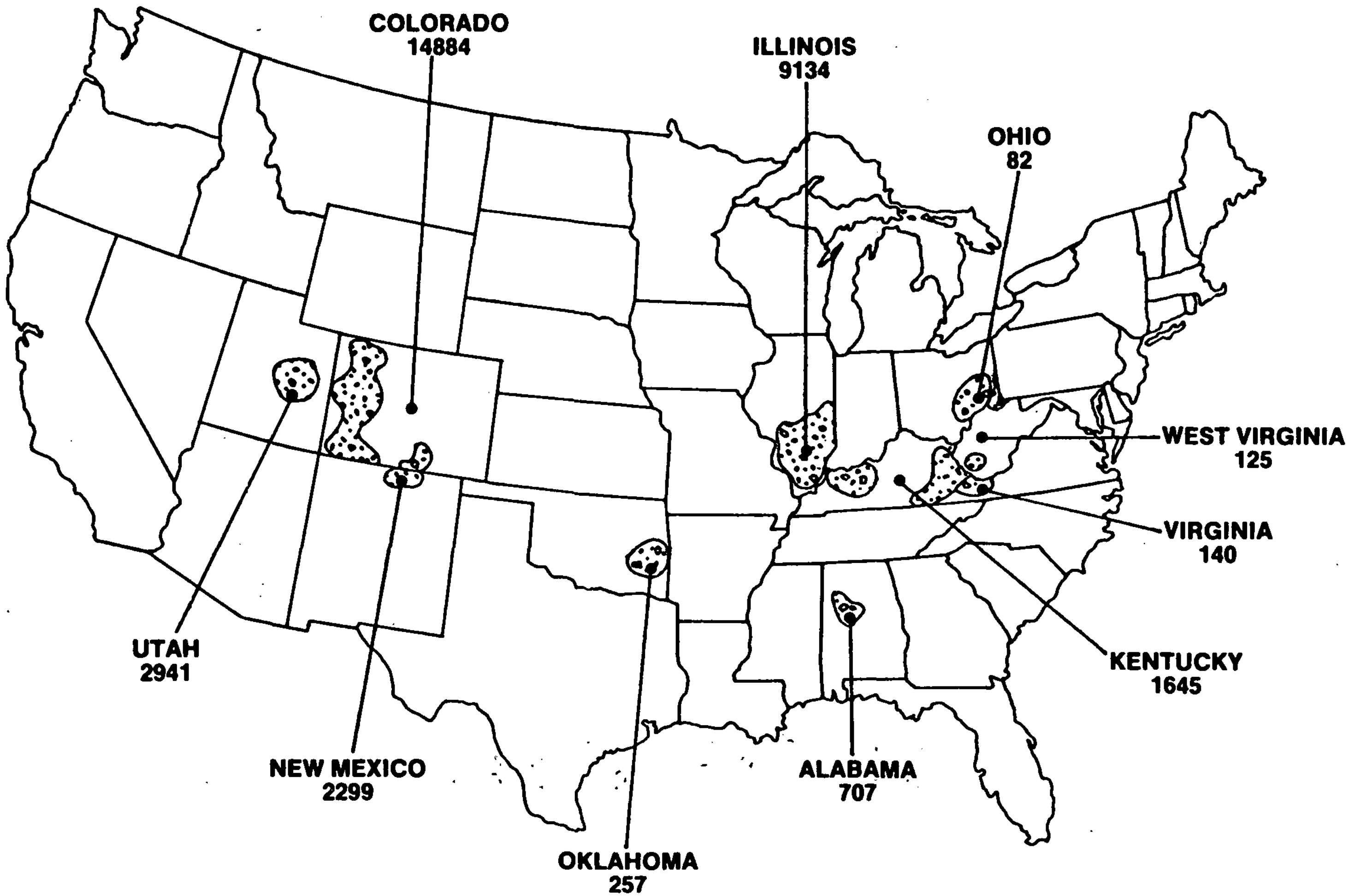
SUMMARY

(ALL FIGURES IN MILLIONS OF TONS)

STATES	TOTAL COAL RESOURCE ≥ 42" IN THICKNESS	TOTAL COAL AMENABLE TO UCG	UCG COAL BENEATH FEDERAL LANDS	UCG COAL BENEATH STATE LANDS	UCG COAL BENEATH TRIBAL LANDS	COAL AMENABLE TO UCG UNDER 300'-500' OF OVERBURDEN	COAL AMENABLE TO UCG UNDER GREATER THAN 500' OF OVERBURDEN	COMMENTS
ALABAMA	706.7	706.7				•	•	
COLORADO	22,208.0	14,883.5	11,415.7	75.0	131.3	•	•	
ILLINOIS	36,243.3	9,133.5				2,820.5	6,313.0	
KENTUCKY	14,269.7	1,645.2	320.0	75.0		939.8	705.4	
NEW MEXICO	2,458.6	2,298.8				•	•	
OHIO	1,715.6	82.2				74.7	7.5	
OKLAHOMA	1,656.0	256.9	41.3		41.3*		256.9	
UTAH	4,079.3	2,941.1	2,522.1			•	•	
VIRGINIA	478.1	139.6					139.6	
WEST VIRGINIA	1,402.9	125.0				65.2	59.8	
TOTAL	85,218.2	32,212.5	14,299.1	150.0	172.6			

• SEE INDIVIDUAL STATE DATA SHEET(S).

Figure 2.1-2
UCG AMENABLE BITUMINOUS COAL RESOURCES
(Figures in Millions of Short Tons)



2.1.5 UCG AMENABLE BITUMINOUS RESERVES EAST OF THE MISSISSIPPI WITH DIP GREATER THAN 30 DEGREES

A. EXPLORATION PROCEDURE

Since the NCRDS data base does not indicate the dip of the coal deposits listed, the exploration procedure to identify UCG amenable bituminous coal with dip >30 degrees began with general public documents on coal deposits. Much of the information was obtained from telephone contacts with state geological survey personnel, review of unpublished Ph.D. dissertations, and review of state geological survey file data. Personal visits were made to the geological survey offices of many of the eastern states containing steeply dipping bituminous coal reserves. File data was researched to further identify the resources.

A list of criteria for evaluating the UCG amenability of the various steeply dipping coal deposits was prepared. After analyzing the amenability of each deposit, a catalog of the total amenable coal deposits with dip greater than 30 degrees was made.

The evaluation criteria for assessing the amenability of steeply dipping bituminous coal beds are similar to those developed for flat-lying beds. The major criteria include:

1. General or regional dip greater than 30 degrees.
2. Minimum of 3.5 million tons of amenable coal.
3. Minimum reported seam thickness of 24 inches.
4. Minimum overburden of 300 feet and maximum overburden of 1,500 feet.

Since mining interest in coal beds with dips greater than 30 degrees is quite low, there is a general lack of published data for this resource. As a result, the tonnage estimates and resource descriptions should be used for purposes of comparison only.

B. RESULTS

Although there is a general lack of data on eastern bituminous coal seams with a dip greater than 30 degrees, initially nine eastern states were identified as containing such resources:

1. Alabama
2. Kentucky
3. Maryland
4. Michigan
5. North Carolina
6. Pennsylvania
7. Tennessee
8. Virginia
9. West Virginia

However, after additional research was conducted and the contacts made with the various state geological surveys to determine the extent of information available for bituminous coal deposits with dips greater than 30 degrees, three states were eliminated - Maryland, Michigan, and West Virginia.

A general description of the steeply dipping bituminous coal deposits in Alabama, Kentucky, North Carolina, Pennsylvania and Virginia, along with comments about the resources in the states that were eliminated, is presented in Section 6.0 of the Phase I report.

Table 2.1-5 summarizes the results of the evaluation.

The major conclusion is at this point, existing data does not indicate significant (3.5 million tons) quantities of steeply dipping bituminous coal in the eastern United States. However, if interest continues in the application of UCG technology to steeply dipping bituminous resources, areas meriting

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TABLE 2.1-5

UCG DATA SHEET

STEEPLY DIPPING BITUMINOUS RESOURCES OF THE EASTERN UNITED STATES

(ALL FIGURES SHOWN IN MILLIONS OF TONS)

STATE/FIELDS	TOTAL COAL RESOURCE ≥ 24" IN THICKNESS	TOTAL COAL AMENABLE TO UCG	UCG COAL BENEATH FEDERAL LANDS	UCG COAL BENEATH STATE LANDS	UCG COAL BENEATH TRIBAL LANDS	COAL AMENABLE TO UCG UNDER 300-500' OF OVERBURDEN	COAL AMENABLE TO UCG UNDER GREATER THAN 500' OF OVERBURDEN	COMMENTS
ALABAMA								
CAHABA FIELD	A	A						
COOSA FIELD	10.6	0						
WARRIOR FIELD	A	A						
KENTUCKY	1.0	0						
NORTH CAROLINA	A	A						
PENNSYLVANIA								
CHESTNUT RIDGE	10.0	0						
BROADTOP FIELD	A	A						
TENNESSEE	B							
VIRGINIA								
RICHMOND BASIN	A	A						
VALLEY COAL FIELDS	A	A						

A EXISTING DATA DOES NOT INDICATE SIGNIFICANT COAL RESOURCE WITH DIP OF AT LEAST 30 DEGREES. FIELD EXPLORATION MAY REVEAL PRESENCE OF ADEQUATE RESOURCES.

B NO ESTIMATE OF RESOURCES AVAILABLE. UNDERGROUND MINE FIRE IN AREA OF OCCURRENCE PRECLUDES DEVELOPMENT FOR UCG.

detailed field investigations include the Coosa Field of Alabama (10.6 million tons of steeply dipping coal ≥24 inches thick) and the Chestnut Ridge Area of Pennsylvania (10.0 million tons ≥24 inches thick).

The general lack of interest to date in the commercial development of steeply dipping bituminous reserves may simplify lease acquisitions. Competition with mining firms may be minimal and royalties may be less than would be required for flat-lying seams.

2.1.6 SITE SELECTION

A. EXPLORATION PROCEDURE

Counties listed in the NCRDS as containing >250 million tons of bituminous reserves were reviewed for potential UCG sites. Careful review of published data resulted in the identification of seventeen counties in four states with potential for future UCG development. Each target area was individually evaluated in the field and detailed as far as possible without actual drilling. Topographical maps were acquired. Markets in the vicinity of target areas were identified.

The criteria which were used for site selection are listed below:

1. Minimum overburden thickness of 300 feet.

2. Minimum of 3.5 million tons of coal available for each site within each target area.

3. Minimum distance of one mile from populated areas (100 or more inhabitants).

4. Minimum distance of one-half mile from major faults.

5. Very little, if any, oil and gas development.

6. Minimum distance of one mile from major rivers and lakes.

7. Minimum distance of one-quarter mile from major federal and state highways and railroads.

Each target area contains far in excess of the 3.5 million tons of coal set forth as the minimum resource necessary to fuel a

25 megawatt electrical generating station for a lifetime of 20 years. Therefore, within each target area more than one UCG project could be sited depending on the results of detailed site evaluations.

B. RESULTS

Table 2.1-6 summarizes the 16 target areas initially determined to be potentially amenable to a UCG project in the four states considered - Illinois, Kentucky, Ohio, and West Virginia.

Based on individual field inspections, the following target areas were deemed suitable for UCG:

Illinois:	IL-3	IL-5
	IL-4	IL-6
Kentucky:	KY-2	
Ohio:	OH-1	
	OH-2	

County maps delineating these target areas appear in Figures 2.1-3 to 2.1-5.

Target area KY-2 needs further investigation. Site OH-2 in Ohio needs much more drilling data to adequately characterize the underlying coal resource. This site was identified on the basis of one deep boring completed by the Ohio Geological Survey.

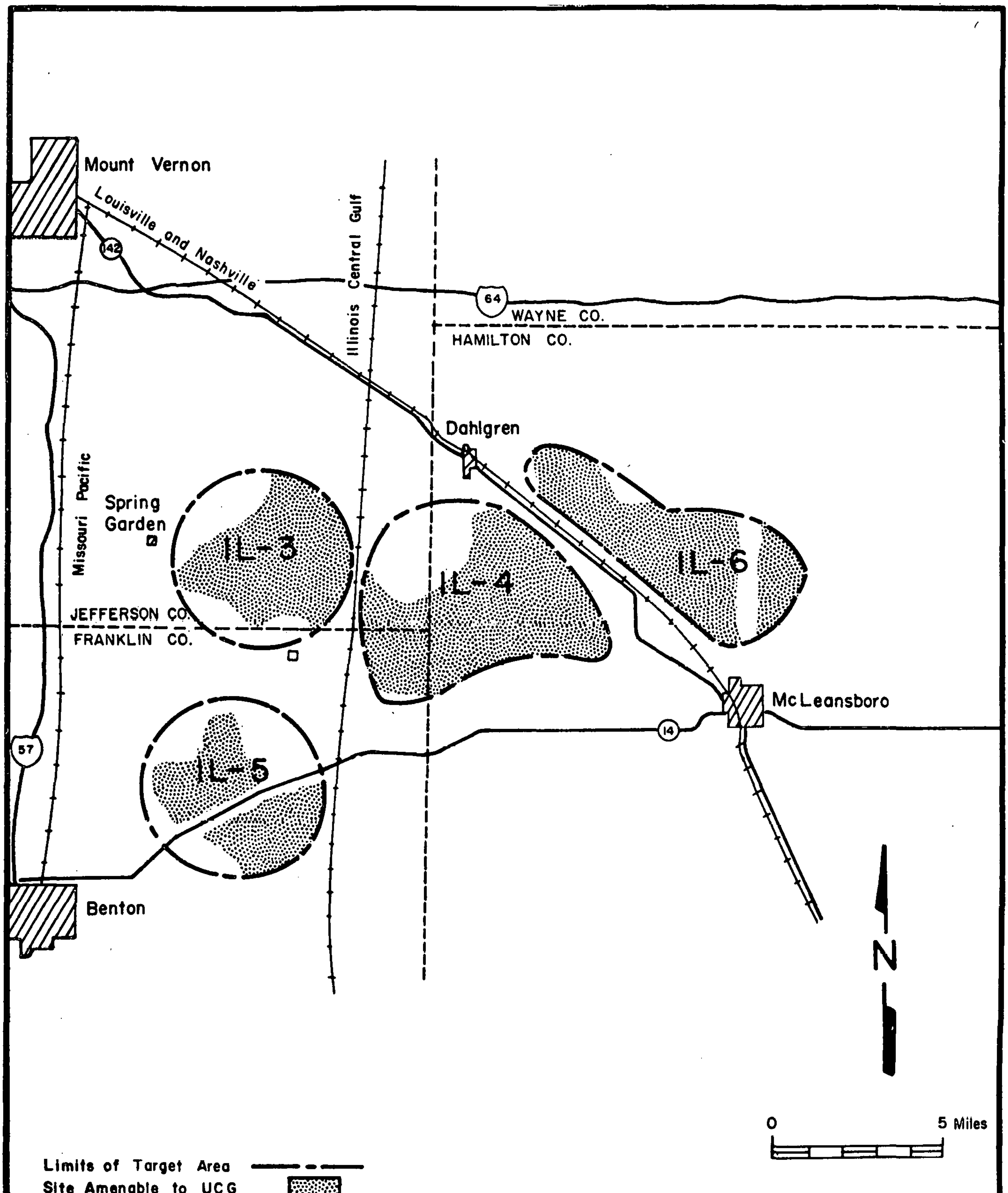
The target areas will require detailed site characterization studies prior to final site selection.

Table 2.1-6
STATUS OF POTENTIAL UCG SITES

State	Target Area	Counties	Seam(s)	Suitability for UCG	Comments
Illinois	IL-1	Logan	Harrisburg - Springfield (No. 5)	Unsuitable	Overburden <300 feet thick.
	IL-2	Logan; Sangamon	Harrisburg - Springfield (No. 5)	Unsuitable	Consolidated overburden is thin. Some areas have <300 feet total overburden.
	IL-3	Jefferson; Franklin	Herrin (No. 6) Harrisburg - Springfield (No. 5)	Partially Suitable	Jefferson County portion of target area is amenable.
	IL-4	Hamilton; Jefferson; Franklin	Herrin (No. 6) Harrisburg - Springfield (No. 5)	Suitable	This target area is sparsely settled, heavily wooded.
	IL-5	Franklin	Herrin (No. 6) Harrisburg - Springfield (No. 5)	Suitable	Currently no mining activity in the area.
	IL-6	Hamilton	Herrin (No. 6) Harrisburg - Springfield (No. 5)	Suitable	Very flat topography.
Kentucky	KY-1	Muhlenberg	Herrin	Unsuitable	No areas of consistently thick coal with minimum 300 feet of overburden.
	KY-2	Webster; Union	No. 11	Suitable	Coal is too deep for mining under current economic conditions.
	KY-3	Pike	Bringham		Sparsely populated area of rugged topography.
Ohio	OH-1	Monroe	Upper Freeport (No. 7) Middle Kittanning (No. 6)	Suitable	Much of target area is sparsely populated.

Table 2.1-6 (Continued)

State	Target Area	Counties	Seam(s)	Suitability for UCG	Comments
Ohio (Cont'd)	OH-2	Washington	Upper Freeport (No. 7) Middle Kittanning (No. 6) Lower Kittanning (No. 5)	Partially	Areas beneath federal land in Wayne National Forest likely not available. Needs much greater amount of drilling data to prove reserves.
	OH-3	Noble; Washington	Middle Kittanning (No. 6)	Unsuitable	Many new oil and gas wells.
West Virginia	WV-1	Roane	Stockton - Lewiston	Unsuitable	Underlying gas field currently being developed.
	WV-2	Lincoln; Logan	No. 2 Gas	Unsuitable	Underlying gas field currently being developed.
	WV-3	Calhoun	No. 2 Gas	Unsuitable	Oil, gas wells present. Drill logs do not indicate presence of coal.
	WV-4	Braxton	Sewell	Unsuitable	Oil, gas wells present. Also 10 underground mines operating in vicinity of target area.



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A Resource Sciences company
TULSA, OKLAHOMA

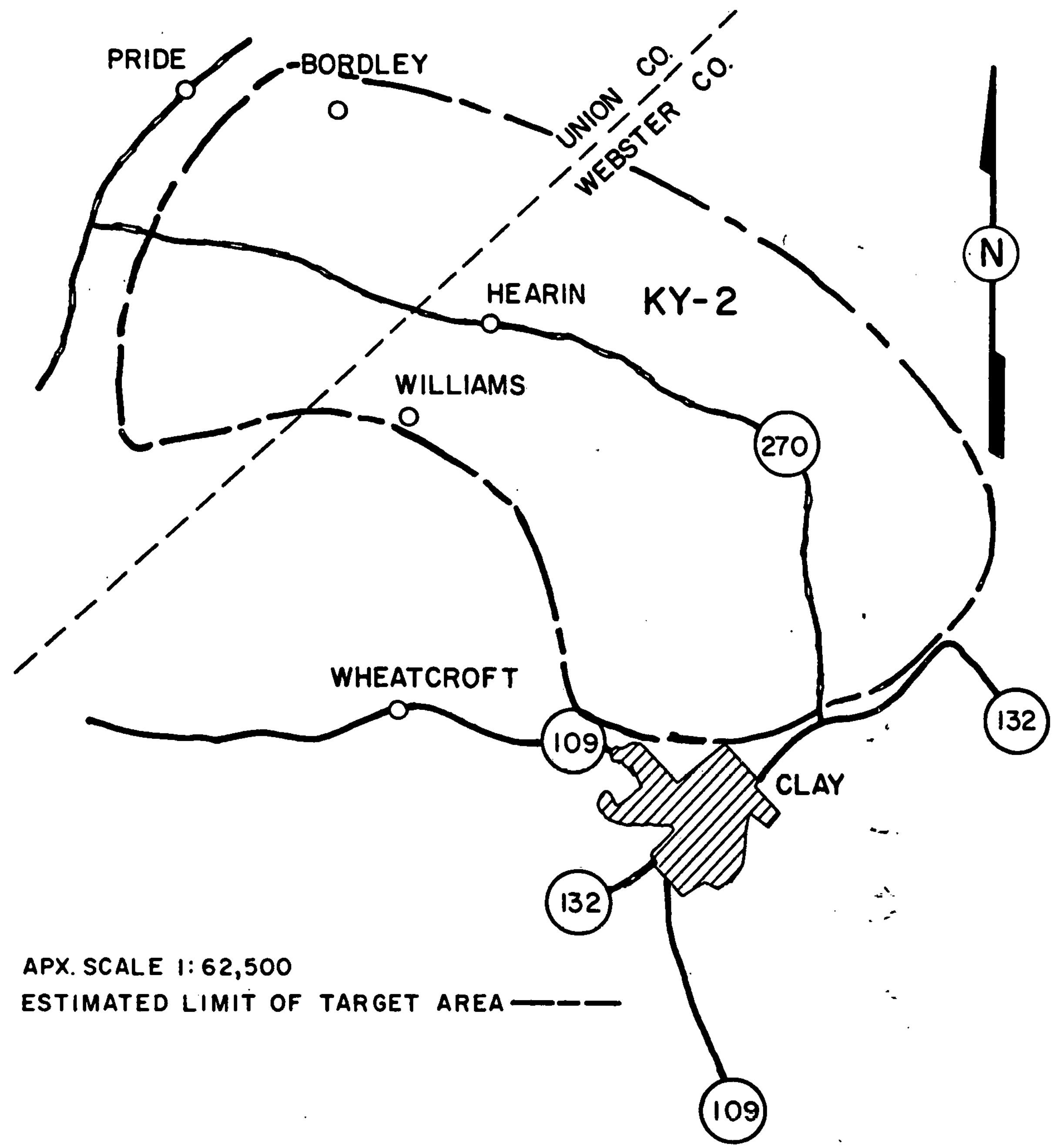
Target Areas IL-3, 4, 5, 6

Date Nov., 1980

Approved

Figure 3.7-3

DES-F-A1000



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A Resource Sciences company

TULSA, OKLAHOMA

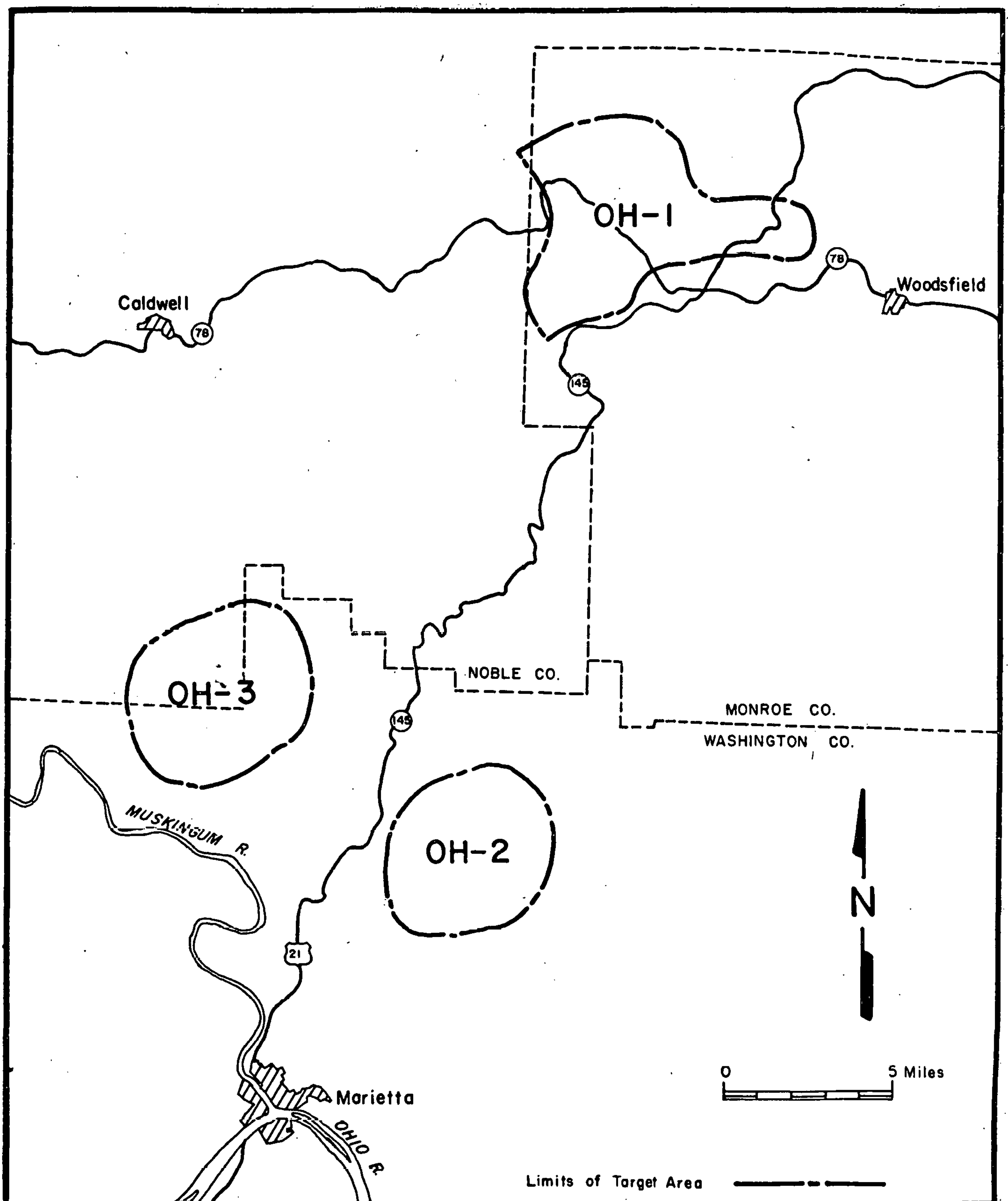
Target Area KY-2

Date June, 1981

Approved

Figure 3.7-5

DES-F-A1000



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TULSA, OKLAHOMA

Target Areas OH-1, 2, 3

Date Nov., 1980

Approved

Figure 3.7-7

DES-F-A1000

2.1.7 POTENTIAL UCG PRODUCTS AND MARKETS

Section 8.0 of the Phase I report identifies potential products and markets for future UCG facilities. Markets near the target areas which were described in Section 7.0 and listed in Table 2.1-6 were considered.

A variety of UCG derived products were examined which include:

1. Low BTU gas (LBG);
2. Medium BTU gas (MBG); and
3. Synthesis gas from which methanol, ammonia, SNG, synthetic crude, hydrogen, carbon dioxide, and carbon monoxide can be produced.

It was concluded that of the two possible product gases, LBG and MBG, MBG is the most versatile because of better economics for pipeline transportation. Additionally, MBG has a higher heating value than LBG, making it more acceptable by a larger share of industries.

The most logical use for UCG product gases in the eastern U.S. may be to generate power on-site using a combined-cycle or co-generation system. A gas turbine based power generator has certain advantages over a conventional coal fired steam turbine power plant. These advantages include modularization, higher efficiency, lower installed cost per kilowatt, less construction time, and less environmental impact.

As Table 2.1-7 indicates, there are several existing energy consumers near the target areas. The KY-1 target area is in Muhlenberg County, the Chamber of Commerce of which responded to a written inquiry in an extremely positive manner. The OH-2 and 3 areas may require that a pipeline cross the Muskingum

TABLE 2.1-7

SUMMARY OF MAJOR INDUSTRIAL AND UTILITY ENERGY CONSUMERS NEAR TARGET AREAS

Target Areas	Existing Natural Gas Consumers		Existing Power Plant Units[1)]	
	No.	Total MCF/yr	No.	Total MW
IL-1	4	19,029,543	1	680[2)]
IL-2	4	31,854,575	4	1065[3)]
IL-3,4,5,6	0	---	0	---
OH-1	2	6,153,157	3	2416
OH-2,3	2	6,153,157	3	3090
KY-1	1	2,246,096	1	220
KY-2, 3	0	---	0	---
WV-1,3	3	19,309,903	3	3256
WV-2,4	3	19,309,903	0	---

1 All Power plants are coal fired steam turbine units except as noted.

2 Includes 230 MW oil fired steam turbine.

3 Includes 77 MW oil fired gas turbine.

that a pipeline cross the Muskingum River and/or the Ohio River.

Other target areas which have both industry and power plants within a 50 mile radius are as follows: IL-1, IL-2, OH-1, WV-1 and WV-3.

Sites such as IL-3, 4, 5, and 6, which are not in industrial areas, will either need to produce transportable fuels such as SNG or methanol, or at least high grade MBG into a 350+ BTU/SCF product by carbon dioxide removal. Industrial complexes such as St. Louis are within a 100 mile radius.

The East-North-Central Census Region is the most logical section of the country to site an alternate fuels project based on underground gasification of bituminous coal. Potentially amenable coal resources, high prices for fuel oil and natural gas, and a large imported energy flow form the basis for this conclusion.

A site could be chosen almost anywhere in the Illinois and Ohio area where amenable UCG coal has been identified due to the existence of existing transportation or transmission systems. The potential radius of up to 150 miles for an upgraded MBG gas using a new pipeline would put Columbus and Pittsburgh in range of OH-1 and St. Louis within range of IL-4, 5 and 6. However, the closer a site could be located to its intended market, the better the chances for economic parity with competitive fuels.

The marketing study also concluded that methanol has an excellent potential as a marketable product; however, the economics of scale required to produce methanol at a competitive price may dictate production in the Western states using sub-bituminous coals.

The marketing study concludes by stating that UCG technology needs to be demonstrated and the potential economic viability determined at a site in the East-North-Central U.S. which has commercially viable quantities of amenable bituminous coal before utilities or industry will show significant interest. To bring about timely adoption of the technology, state or federal governments will need to sponsor the basic research and initial field testing.

2.2 CONCEPT EVALUATION - PHASE II REPORT

2.2.1 INTRODUCTION

The Phase II report of the Assessment of Underground Coal Gasification in Bituminous Coals - Identification, Evaluation and Ranking of Gasification Concepts includes the following major sections:

Section 4.2 is a general discussion of economic and technical considerations of UCG. A section on concept identification is included which provides the basis for Section 4.4 - Technical Evaluation.

Section 4.3 presents an historical account of laboratory and math modeling work specific to UCG in bituminous coal.

Section 4.4 is a major section in the Phase II report presenting details of linking and gasification concepts. One of the principle results was a numerical evaluation of the various concepts based on a set of established criteria.

Section 4.5 contains estimated costs for linking and drilling per million BTU's of gas energy produced for each concept with any significant future potential. Two seam thicknesses, 4 feet and 8 feet, and four depths, 500, 1000, 2000, and 3000 feet were evaluated.

Section 4.6 ranks UCG concepts using a numerical rating scheme for technical evaluation and estimated costs.

2.2.2 OBJECTIVES

The Phase II report of the Assessment of Underground Coal Gasification in Bituminous Coals - Identification, Evaluation and Ranking of Gasification Concepts has the following major objectives:

1. Review literature specific to UCG to identify concepts and procedures for application of UCG to swelling bituminous coals.

2. Evaluate the technical and economic advantages and disadvantages of the identified UCG techniques as applied to swelling bituminous coals.

3. Estimate the relative probability of success for application of the identified and evaluated UCG concepts when applied to swelling bituminous coals.

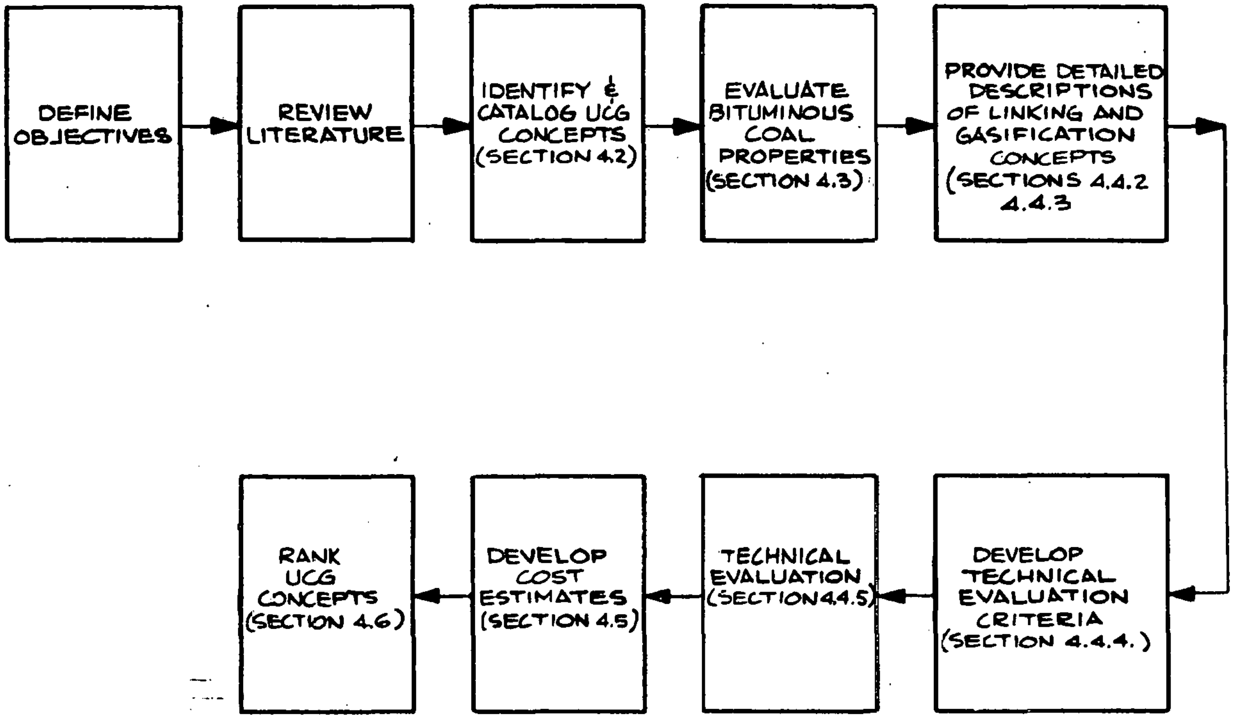
2.2.3 CONCEPT IDENTIFICATION

The methods used to identify and evaluate UCG concepts are diagramatically shown in Figure 2.2-1 and include:

1. Definition of a set of objectives.
2. Literature review of laboratory and bench-scale studies, mathematical modeling studies, and field tests of UCG.
3. Identification and cataloging of UCG processes.
4. Preparation of a concise review of bituminous coal properties.
5. Preparation of a detailed description of the identified and cataloged linking and subsequent gasification methodologies.
6. Development of a set of concept evaluation criteria.
7. Development of cost estimates for linking and vertical wells.
8. Preparation of a technical ranking of linking concepts with comparison cost estimates.

A. LITERATURE REVIEW

The literature review was extensive, covering nearly all of the major literature on UCG. The U.S. publications are the most complete and well written documents. The Soviet references, while often inconsistent and vague, provide many useful accounts of field tests and theory. While there is an enormous quantity of literature available on UCG, unfortunately, very little of the early work had the benefits of modern data acquisition and analytical equipment. Hence, much of the early British, Soviet, and American work in UCG is very qualitative. Recent work, reported in the Annual UCG Symposia, is perhaps the best public information available anywhere on UCG.



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A Resource Sciences company
TULSA, OKLAHOMA

PHASE II DEVELOPMENT FLOW SHEET

Date DSB 11-25-81
Approved

FIGURE 2.2-1

B. TECHNOLOGY OVERVIEW

B.1 CONCEPT SCREENING

As a result of the literature review, a number of concepts were identified. In order to reduce the number of concepts to a manageable number they were grouped according to generic form. Table 2.2-1 presents the composite listing of the concepts as grouped.

TABLE 2.2-1
IDENTIFIED UCG CONCEPTS

Gasification Methods	Linking Methods	Auxiliary Methods
Blind Borehole	Chemical Comminution	Gamma-Ray Heating
Open Borehole	Directional Drilling	Calcined-Lime Injection
Broad-Front	Electrolinking	Catalyst Injection
Linked Vertical Wells	Explosive Fracture	Non-Oxygen Reactants
Packed Bed	Hydraulic Fracture	Induction Heating
Pressure Change	Laser	
	Pneumatic	
	Reverse Combustion	
	Shaped-Charge	
	Steam Fracture	

Concept grouping is broken in three parts as follows:

1. Gasification Methods
2. Linking Methods
3. Auxiliary Methods

Gasification methods focus attention on the relationship between the injection and product gas streams. For example, in the linked vertical well concept of gasification, injection blast is directed into one vertical well which has been linked to another vertical well through which product gases are collected. In the blind borehole concept, blast is directed to the coal seam through a pipe which is contained inside of an outer casing. The product stream is withdrawn through the annular space between the injection pipe and the outer casing.

Linking concepts focus attention on methods of achieving enhanced permeability through a coal bed between injection and production wells. The native gas flow capacity (permeability) of a bituminous coal seam is generally low, on the order of less than 10 millidarcies, requiring permeability enhancement. Enhancement techniques are used with the linked vertical well concept for this gasification concept to be successful. Adequate gas flow must be established through the coal bed between the injection and production wells.

Auxiliary methods are techniques for enhancing the gasification process and are generally not link concept specific nor are they coal type specific. While they may ultimately be used in actual operation they are not considered necessary for the evaluation of UCG in bituminous coal.

Investigation of the above methods revealed the concepts listed in Table 2.2-2 warranted further evaluation. Certain methods were eliminated from detailed discussion due to very low

TABLE 2.2-2

EVALUATED UCG CONCEPTS

A. Linked Vertical Wells (LVW).

1. Hydraulic Fracturing.

a. By itself.
b. Followed by Electrolinking.
c. Followed by Reverse Combustion Linking (RCL).
d. Followed by Chemical Comminution.
e. Followed by Explosive Fracturing.

2. Shaped Charge.

a. By itself.
b. Followed by Hydraulic Fracturing.
c. Followed by Electrolinking.
d. Followed by RCL.

3. Pneumatic Fracturing

a. Followed by RCL.

4. Electrolinking.

B. Blind Borehole.

1. Directional Drilling.

a. From Surface.
b. From Partial Mine.

C. Open Borehole.

1. Directional Drilling.

a. From Surface.
b. From Partial Mine.
c. Coflow.
d. Reverse Flow.

D. Broad Front.

1. Line Drive.

technical viability; however, these methods were put on concept screening forms and combinations of several were evaluated.

Concept screening forms were used to establish a data base for further concept evaluation. These forms include:

1. Name of UCG concept
2. Brief concept description
3. Source of information
4. Applicability
5. Brief history

B.2 CONCEPT DETAILING

The concepts briefly evaluated in the initial screening forms were evaluated in detail in Section 4.4 of the Phase II report. The major considerations encountered in all UCG applications were identified and discussed. They are listed as follows:

1. Economic
    a. Seam depth
    b. Seam thickness
    c. Sweep efficiency
    d. Product gas heating value
    e. Flow rates, injection and production
    f. Oxygen utilization
    g. Gas loss
    h. Environmental

2. Technical
    a. Reaction kinetics
    b. Fluid flow
    c. Coal and overburden properties
    d. Structural/mechanical properties
    e. Process simulations

3. Historical
   a. Laboratory and bench-scale results
   b. Field testing results

These concept detailings constitute a major portion of the Phase II report. A complete reference list is contained at the end of each discussion section.

C. UCG TECHNOLOGY SPECIFIC TO BITUMINOUS COALS

The work completed to date on UCG technology specifically applied to bituminous coals was determined. Math modeling, laboratory studies, and field tests specific to UCG of bituminous coals were reviewed. A brief summary of these topics follows.

C.1 MATH MODELING

A review of the math modeling literature indicates no field tests, other than the recent Pricetown field test, have provided data adequate for modeling of bituminous UCG reactors. As a result, no extensive UCG models, other than the theoretical development of structural aspects of bituminous UCG, have been developed for bituminous coal applications.

The math modeling efforts for non-bituminous coals are important since much of the methodology used to model lower rank coals should be useful in bituminous applications. These efforts have focused on the prediction of the following:

1. Product gas compositions
2. Temperature distributions
3. Subsidence effects
4. Flame front velocity

5. Effects of changing process variables
6. Sweep efficiency
7. Effects of water influx
8. Effects of spalling and drying
9. Cavity growth
10. Viscoelastic effects

C.2 LABORATORY STUDIES

The laboratory studies conducted in the context of UCG of bituminous coals can be grouped into four categories as follows:

1. Kinetic studies
2. Property studies
3. Structural/mechanical studies
4. Process simulations

Kinetic studies include pyrolysis and reaction-controlled gasification. Results have shown that pyrolysis of bituminous coal produces less gas than pyrolysis of subbituminous coal. There is some evidence that at high heating rates, the temperature profile is steep and only a narrow layer of coal becomes plastic, resulting in reduced block swelling. On the other hand, low heating rates can cause massive block swelling.

Property studies have been carried out to determine transport and mechanical properties of bituminous coals. Properties studied include thermal conductivity, specific heat, thermal expansion, density, compressive and tensile strength, porosity, and permeability.

Mechanical properties of bituminous coal under both uniaxial compression and shear have been studied. Behavior studied included: basic stress vs. strain, stress-relaxation, creep, viscoelasticity, time-dependency, and expansion.

Laboratory process simulations have been conducted in open channels, open cavities, single fractures, and in porous media.

C.3 FIELD TESTS

Field testing of UCG concepts as applied to bituminous coal deposits has not been as extensive as in subbituminous and other lower rank coals. The reason for the emphasis on lower rank coals in the U.S. field testing efforts has been due to the availability of thick seams at shallow depths. Additionally, lower rank coals shrink and crack during pyrolysis which tends to promote permeability, whereas, most bituminous coals tend to swell and plug during heating. Therefore, U.S. field testing efforts have principally been directed at solving the technical problems of subbituminous coal beds before atempting bituminous coals.

The Soviets and the British have conducted field tests in bituminous coal with varying degrees of success. Most of the work was done during the 1940-1960 period and was without the aid of modern data acquisition and analysis equipment. However, the testing at Newman Spinney in England and at Lisichansk in the USSR indicate that UCG of bituminous coal is a distinct possibility in spite of major technical difficulties.

U.S. field testing of UCG concepts in bituminous coal began at Gorgas, Alabama. Hydraulic fracturing, electrolinking-carbonization, reverse combustion linking, and forward gasification in the linked vertical well mode were all tested. The results in most cases were inconclusive due to gas leaks.

Plugging due to swelling and tar condensation were also encountered during forward burns.

It was not until the field test at Pricetown, West Virginia that the U.S. conducted its first experiment in a deep (900-feet) bituminous coal bed. This test used pneumatic fracturing with reverse combustion linking. Problems with plugging were encountered and only a short forward gasification period was sustained; however, a product gas with an average higher heating value of 124 BTU/SCF was made using air only as injectant.

2.2.4 EVALUATION

A. TECHNICAL EVALUATION

It was apparent following the concept detailing that a completely quantitative technical evaluation of UCG concepts was not possible. Judgement must be introduced in making the comparisons. These judgements follow from considering the performance of the various UCG concepts reported in the literature. The volume of the reporting on the concepts depends on the extent of the laboratory work, field testing and commercial operation which have been done. The completeness of the reporting also varies widely, with the work reported by the U.S. being the most complete and the most readily available. To evaluate the various concepts in a consistent manner the following six categories of performance criteria were considered:

1. Resource Recovery
2. Criteria Related to Resource Properties
3. Previous Experience
4. Safety Considerations
5. Other Contributions or Advantages
6. Other Problems/Risks/Disadvantages

Each of these six criteria is explained below:

1. Resource Recovery

The performance of a concept was rated from +3 (very good) to -3 (very bad) for the following operating characteristics.

a. Sweep Efficiency
b. Gas Losses
c. Override
d. Channeling
e. Controllability
f. Directionality
g. Heating Value

2. Effect of Resource Properties

The ability of a concept to cope with resource properties was rated from +3 to -3 with regard to:

a. Permeability
b. Swelling
c. Liquid Plugging
d. Water Influx
e. Ash in Coal Seam

3. Previous Experience

No experience was rated zero while successful operation through laboratory, field pilot and commercial projects was ranked plus three. A very unsuccessful previous experience was ranked minus three.

4. Safety Considerations

The rating under this category was influenced mostly by the need to do underground mining or handling of high explosives.

The UCG processes which require underground mining for site preparation are considered more hazardous than processes which are operated from the surface. All of the

UCG concepts involve possible escape of toxic gases, corrosion of piping and the handling of the combustible materials. Pressure could be included in this evaluation but the handling of high pressure gases is common in industry and was not considered a detriment to a UCG operation.

5. Other Contributions or Advantages

A concept with a unique advantage was rated from 1 (low) to 3 (high) and assigned a probability with which the advantage would be expected to occur ranging from 1 (low) to 3 (high). For example, a blind borehole is unique in that the air injection tube also serves as a heat exchanger and improves the efficiency of the blind borehole UCG concept.

6. Other Problems/Risks/Disadvantages

A concept could have unique disadvantages or risks which would detract from its reliability in a UCG operation. The characteristic was rated from -1 (low) to -3 (high) and a probability assigned to the possible occurence of the undesirable event. For example, in the case of a blind borehole the coal seam could collapse around the air tube and block off the production annulus.

B. COST EVALUATION

Costs were developed as a basis for economic comparison of various linking methods and gasification concepts. Costs were developed for only those methods and concepts which were not screened out for lack of technical viability.

The cost factors were researched in sufficient depth to make the costs suitable as a basis for comparison and ranking of concepts. The level of effort in researching linking method costs was greatest for the methods considered most viable.

Cost estimates were prepared for the following linking methods:

1. Hydraulic fracturing
2. Shaped charges
3. Pneumatic linking
4. Electrolinking
5. Directional drilling
6. Reverse combustion
7. Steam fracturing
8. Chemical commination
9. Explosive fracturing

Comparison costs were limited to the cost of vertical wells plus the cost of linking. The comparison costs are the costs of creating operable in situ gasification reactors. These are valid bases for comparison if the gasifier operating costs and the above grade gas clean-up and processing costs do not vary greatly from one concept to another.

Various parameters of coal properties, process data and operating cost factors were standardized in the cost evaluations to facilitate comparisons. Factors such as extraction efficiency, thermal efficiency and gas losses were also standardized on the basis that expected differences in these factors would be considered in the concept ranking section.

Costs were generally developed for standard seam thicknesses of 4-feet and 8-feet and standard seam depths of 500-feet, 1000-feet, 2000-feet and 3000-feet. Exceptions were the partial mining concepts.

Costs are based on patterns in which the pattern width was limited to 10 times the seam thickness, not more than 80 feet for 8 foot seams or 40 feet for 4 foot seams.

Well spacings were selected for each concept based on expected attainable linking distance.

2.2.5 DISCUSSION OF RESULTS

A. GENERAL

Review of the literature in the areas of math modeling, laboratory studies, and field testing of UCG concepts in bituminous coal beds has revealed that major technical problems exist but the technology holds significant potential. In situ gasification of deep bituminous coal deposits may be the only viable technique to utilize those energy deposits.

Laboratory investigations conducted at the University of Alabama by McKinley and others is an excellent beginning. These and other studies have shown that forward combustion as it is now conducted in fractured bituminous coal beds is susceptible to plugging due to liquid condensation and swelling. However, these studies indicate that reverse combustion linking is a viable technique for dealing with swelling but is limited by poor areal sweep.

Math modeling of UCG regardless of coal rank is a complex problem. But the problems are particularly acute with bituminous coal. The problems of water influx, subsidence, heat and mass transfer, viscoelastic effects, ash diffusion and changing reactor characteristics will all have to be addressed probably in a complete three dimensional model.

Field testing of UCG concepts have illustrated the site specific nature of UCG, a situation similar to enhanced oil recovery operations. Results indicate the need to conduct future field tests at sufficient depth to control gas losses, minimize subsidence and limit water influx.

The Newman Spinney test P-5 showed that sustained underground gasification of bituminous coal is a distinct possibility. The tests at both Gorgas and Newman Spinney were challenging but were inconclusive due primarily to poor sites. This indicates the importance of complete site evaluation prior to a field test.

The Pricetown test indicates in situ gasification of bituminous coal is certainly possible but the plugging problem will have to be solved before commercialization can be realized. The open borehole concept may be the answer to this problem but only a full field test will prove it.

For the open borehole linking concept to succeed, directional drilling control will have to be successfully applied to thin deep coal seams. Directional drilling control technology has improved over the last five years and will continue to improve due to increased use in methane drainage, under river crossings, and offshore platform directional drilling.

B. TECHNICAL EVALUATION

Gasification concepts which were evaluated include:

1. Linked vertical well (LVW)
2. Blind borehole
3. Open borehole*
4. Broad front

*While the Open Borehole in its simplest form is a linked vertical well it can be varied into more complex forms; such as Reverse Flow which is sufficiently different to justify a separate category.

Linking concepts selected for evaluation include the following:

1. Directional drilling
2. Hydraulic fracturing
3. Electrolinking
4. Reverse combustion
5. Chemical comminution
6. Explosive fracturing
7. Shaped charge
8. Pneumatic fracturing

The linked vertical well and open borehole gasification concepts appear to be the most technically viable. The linked vertical well concept although requiring establishment of a linkage path in the coal bed has been extensively used with apparent success by the Soviets in flat-lying coal seams. This method has also been tested in bituminous coal in the U.S. at Gorgas and Pricetown. The use of one vertical well to supply oxidant to the coal bed while withdrawing product gases from another, appears to be technically feasible. Problems arise in establishing an acceptable linkage path in the coal.

Individual linking concepts and combinations of two linking concepts within the context of the LVW gasification mode were evaluated. Application of a single linking method may not be effective in producing a stable usable link; hence, the combination methods were evaluated. For example, hydraulic fracturing using intense water flushing of the induced fracture system followed by air drying and reverse combustion link enhancement appears to be feasible. The fracture system produced by hydraulic fracturing tends to reclose once fracturing pressure is released but water flushing may widen and enhance permeability. Reverse combustion will preheat the coal bed, widen the fractures further, and hopefully, stabilize the fractures.

Electrolinking preceeded by hydraulic fracturing using an electrolytic fluid could prove effective. Fractures saturated with electrolyte could enhance the electropyrolysis process. Low melting water soluble salts could possibly provide a current path once the water phase boils off. Electrolinking without some enhancement technique is difficult to control. However, electrolinking has the advantage of pyrolyzing coal without requiring native permeability.

Pneumatic fracturing was used at Pricetown but reclosure is a problem and the risk of gas losses due to fracturing of overburden rock is a distinct possibility. Hydraulic fracturing is preferred over pneumatic fracturing due to the eroding ability of fracturing fluids compared to air.

The shaped charge concept has: danger of working with explosives, limited penetration, and possibility of enhancing gas losses.

All of the linking techniques except directional drilling from the surface are strongly dependent on coal bed physical and chemical properties. Hydraulic fracturing is dependent on the native coal permeability, prefracture fluid flow channels and stress/strain parameters. Fracturing techniques are highly influenced by faulting and folding and other inhomogeneities present in the coal bed. Electrolinking also has a strong dependence on coal electrical properties and inhomogeneities. Likewise, reverse combustion depends on native gas flow patterns when used as the primary linking method; however, reverse combustion should be an excellent secondary link enhancement method.

Directional drilling apart from actual mining is the only method offering independence from coal bed properties with the exception of extreme roll across the seam. Drilling contractors are confident current equipment and technology is capable of drilling a horizontal borehole along the bottom of a 4-feet thick flat-lying coal seam 900-feet deep for distances up to 1500-feet. This claim has yet to be field tested for these specifications; however, directional drilling was used with success at the Emerauld Mine degasification test.

Unlike most other gasification and linking concepts in which oxidant contact with the coal is through small cracks and fissures in what is termed "permeation" flow; the open borehole concept involves ignition and gasification along an open borehole in the coal deposit. Open borehole gasification was successfully tested at Hoe Creek III in a subbituminous coal bed and should be feasible in a bituminous coal deposit, but laboratory testing on boreholes in blocks of bituminous coal should preceed any field testing of this concept. It is not certain a combustion front will be stable along a borehole in thin bituminous coals or that areal sweep will be sufficient for economic justification.

The term "open" borehole from the surface refers to the fact that both ends of a borehole drilled horizontally along a flat-lying coal bed are on the surface. This situation then is essentially identical to a linked vertical well concept where the link path is a borehole. Two situations propose themselves in this context:

1. Directional drilling from the surface down to the coal bed, drilling along the coal seam near the bottom for a specified distance, and return by directional drilling to the surface. One end of this borehole becomes the injection "well" the other end the production "well".

2. Directional drilling from the surface down to the coal seam, and drilling along the bottom of the coal seam with directional control used to intercept previously drilled and surveyed vertical wells. The vertical wells are used as injection and production wells.

The open borehole concept is appealing due to the large degree of control over the link direction, the possibility of gasification staying at the bottom of the coal seam, and the likelihood that swelling and liquid plugging problems will be minimal.

The open borehole concept using directional drilling from a partial mine has the basic problem of putting men underground which is economically unfeasible at this time for thin deep seams. The open borehole coflow concept is susceptible to plugging and lost communication due to roof collapse. The reverse flow open borehole concept appears to be an excellent concept; however, after ignition the flame front may proceed by reverse combustion along the injection borehole rather than propagate into the coal bed. This problem, however may be solved by using the CRIP (controlled retraction injection point) system proposed by Lawrence Livermore National Laboratory. In this system a cased horizontal borehole is used to provide oxidant to the coal seam. As roof collapse occurs coincident with gasification, explosive charges are placed in the horizontal casing and detonated, perforating the casing, fracturing and exposing fresh coal for continued gasification. This concept is scheduled to be field tested in Centralia, Washington during a proposed large block test. The CRIP system may be difficult to employ in deep coal seam due to casing installation problems.

The broad front line drive concept offers the possibility of efficient resource recovery, but establishing and sustaining a broad flame front is probably not feasible.

C. COSTS

A brief summary of the cost estimates for the linking methods evaluated appears in Table 2.2-3. The shaped charge linking concept is the most costly based on incremental well costs. Electrolinking is expensive due to the cost of the electrode and power generation equipment.

Directional drilling is more costly than fracturing methods but the greater degree of control over link direction offsets those costs. Directional drilling is expensive due to the sophisticated equipment and trained personnel involved.

A brief summary of directional drilling costs for the open horizontal borehole completion appears in Table 2.2-4.

Quotations were obtained from directional drillers as a basis for estimating costs for directionally drilled wells. The quotations were based on a coal seam 1000 feet beneath the drilling site, with the wells drilled vertically from the surface and deviated at 6°/100' to reach and enter the coal seam horizontally. The boreholes were then drilled for a 1500 foot distance horizontally through the coal seam.

The drilling plans call for drilling the entire measured depth of the holes under directional control using downhole mud motors. The wells would be drilled using a downhole steering tool while monitoring direction from the surface during drilling, in addition to taking periodic multishot well surveys.

TABLE 2.2-3

LINKING COST ESTIMATES

	Linking Concept	Cost Per Link Foot Depth 500'	1000'
1.	Hydraulic fracturing		
	Using gelled water and sand	$ 5	$ 5
	Using water and air drying	4	6
2.	Shaped charge	673	912
3.	Pneumatic linking	2	2
4.	Electrolinking	144	161
5.	Directional drilling	157	161
6.	Reverse combustion	27	59
7.	Chemical comminution	87	88

TABLE 2.2-4

SUMMARY OF OPEN HORIZONTAL BOREHOLE COSTS

WELL CONFIGURATION			
True Vertical Depth	500'	1000'	2000'
Measured Depth Through Overburden	1050'	1550'	2550'
Measured Depth through Coal Seam	1500'	1500'	1500'
Suface Casing Size, OD	9 5/8	9 5/8	9 5/8
Casing through Overburden Size	5 1/2	5 1/2	5 1/2
Hole Size through Coal Seam	4 1/2	4 1/2	4 1/2
Cement Type, Normal or HTR*	Normal	Normal	Normal
Cemented, Full Depth or Multi Stage	F.D.	Multi	Multi
WELL COSTS			
Drilling Costs	$ 96,500	$ 99,000	$ 112,500
Directional Control Costs	101,300	101,050	115,050
Cementing Costs	3,207	3,457	3,457
Casing Costs	7,402	10,928	17,978
Wellhead	2000	2000	3500
Technical and Management Support	25,500	25,500	28,500
Well Cost Per Horizontal Foot $ (For 1500 Horizontal Feet)	157	161	187
TOTAL WELL COST	$ 235,909	$ 241,935	$ 280,985

Vertical well total costs were developed from drilling and completion costs for various depths and production casing sizes. A partial list of these results appears in Table 2.2-5 together with the vertical well costs per million BTU extracted for several different gasifier sizes: 60' x 60', 80' x 80', 150' x 80'.

These vertical well costs were added to the linking costs to produce combination cost estimates for specified gasifier sizes. The combination costs are illustrated in Table 2.2-6.

TABLE 2.2-5
VERTICAL WELL COMPLETION COSTS

WELL DEPTH	CASING OD	TOTAL WELL COST	WELL COST PER FOOT	Cost per 10^6 BTU Extracted — Well Spacing 60' x 60'	80' x 80'	150' x 80'
500'	5 1/2	$ 20,388	$ 40.78	$1.4546	$ .8181	$ .4363
500'	7	24,788	49.58	1.7685	.9947	.5306
500'	8 5/8	29,460	58.92	2.1018	1.1819	.6306
500'	9 5/8	30,893	61.79	2.2040	1.2400	.6611
1000'	5 1/2	35,797	35.80	2.5539	1.4366	.7661
1000'	7	42,876	42.88	3.0589	1.7206	.9176
1000'	8 5/8	50,635	50.64	3.6125	2.0320	1.0838
1000'	9 5/8	53,302	53.30	3.8028	2.1391	1.1408
2000'	5 1/2	75,827	37.91	5.4098	3.0430	1.6230
2000'	7	88,758	44.37	6.3323	3.5619	1.9000
2000'	8 5/8	104,181	52.08	7.4236	4.1809	2.2300
2000'	9 5/8	109,312	54.65	7.7987	4.3867	2.3396

Assumptions:
1) 8' thick seam, 1.4 s.g., 13,880 BTU/lb.
2) 65% extraction, 65% thermal Efficiency, 5% gas loss.
3) January 1982 estimates costs.

PROCESS DIVISION
OF
WILLIAMS BROTHERS ENGINEERING COMPANY
A Resource Sciences Company

TABLE 2.2-6

COMPARISON OF LINKING AND WELL COSTS*
FOR VARIOUS UCG CONCEPTS
($/MMBTU)

A. Linked Vertical Wells	Seam Depth (Ft)	Coal Thickness 8 Ft Link And Well Costs $/MMBTU		Coal Thickness 4 Ft Link And Well Costs $/MMBTU	
1. Hydraulic Fracture		Spacing 80' x 150'		Spacing 40' x 150'	
(a) By itself	500	.72		2.85	
	1000	1.20	Avg. 2.00	4.73	Avg. 8.00
	2000	2.40		9.60	
	3000	3.72		14.81	
(b) Followed by electrolinking	500	1.19		4.73	
	1000	1.73	Avg. 2.60	6.85	Avg. 10.40
	2000	3.04		12.16	
	3000	4.47		17.81	
(c) Followed by RCL	500	.81		3.19	
	1000	1.32	Avg. 2.40	5.48	Avg. 9.60
	2000	2.83		11.32	
	3000	4.71		18.79	
(d) Followed by chemical comminution	500	.94		3.78	
	1000	1.42	Avg. 2.25	5.66	Avg. 9.00
	2000	2.64		10.58	
	3000	3.96		15.79	
(e) Followed by explosive fracture	500	N/A		N/A	
	1000	N/A		N/A	
	2000	N/A		N/A	
	3000	N/A		N/A	
2. Shaped Charge		Spacing 80' x 50'		Spacing 40' x 150'	
(a) By itself	500	3.20		12.70	
	1000	5.00	Avg. 7.80	19.90	Avg. 31.20
	2000	8.90		35.60	
	3000	14.20		56.75	

* These costs include only the well costs (and borehole costs in some cases) and linking costs.

TABLE 2.2-6

COMPARISON OF LINKING AND WELL COSTS (Continued)
FOR VARIOUS UCG CONCEPTS
($/MMBTU)

	Seam Depth (Ft)	Coal Thickness 8 Ft Link And Well Costs $/MMBTU		Coal Thickness 4 Ft Link And Well Costs $/MMBTU	
A. **Linking Vertical Wells** (Continued)					
2. Shaped Charge (Continued)					
(b) With hydraulic fracture					
(c) With electrolink		Would Reduce above costs but are unlikely combinations			
(d) With RCL					
3. Pneumatic		Spacing 80' x 80'		Spacing 40' x 80'	
(a) Followed by RCL	500	1.34		5.36	
	1000	2.25	Avg. 3.75	8.99	Avg. 15.00
	2000	4.51		18.02	
	3000	6.93		27.71	
4. Electrolinking		Spacing 80' x 150'		Spacing 40' x 150'	
(a) By itself	500	1.13		4.52	
	1000	1.67	Avg. 2.55	6.68	Avg. 10.20
	2000	2.98		11.92	
	3000	4.39		17.56	

TABLE 2.2-6

COMPARISON OF LINKING AND WELL COSTS (Continued)
FOR VARIOUS UCG CONCEPTS
($/MMBTU)

	Seam Depth (Ft)	Coal Thickness 8 Ft Link And Well Costs $/MMBTU (Spacing 80' x 150')		Coal Thickness 4 Ft Link And Well Costs $/MMBTU (Spacing 40' x 150')	
B. Blind Boreholes					
1. From surface	500	2.01		8.04	
	1000	2.23		8.92	
	2000	3.03	Avg. 2.85	12.12	Avg. 11.50
	3000	4.19		16.76	
2. From a partial mine	1000	.95		Not evaluated	
C. Open Boreholes					
1. From surface	500	1.31		5.16	
	1000	1.88		7.49	
	2000	3.37	Avg. 3.00	13.51	Avg. 12.00
	3000	5.36		21.50	
2. From partial mine	1000	1.85		Not evaluated	
3. Coflow	500	1.58		6.29	
	1000	2.37		9.37	
	2000	4.43	Avg. 3.80	17.52	Avg. 15.00
	3000	6.90		27.12	
4. Reverse flow	500	1.14		4.54	
	1000	1.60		6.30	
	2000	2.81	Avg. 2.50	11.02	Avg. 9.60
	3000	4.29		16.65	

2.2.6 RANKING

Table 2.2-7 presents the ranking of UCG gasification and linking methods based on technical viability. The combination costs composed of linking plus vertical cost estimates were found not to differ significantly among the methods evaluated.

The technical ranking places linked vertical well and open borehole gasification techniques ahead of the blind borehole and broad front concepts. The blind borehole methods are particularily susceptible to well damage and the broad front concept is probably not feasible.

The open horizontal borehole from the surface ranks as the most technically viable concept for the following reasons:

1. Directional drilling is almost completely independent of coal bed properties allowing control over placement of oxidant and gasifier development.

2. The method is safe and does not require men underground.

3. The method has been successfully tested in lower rank coal.

4. The problem of plugging due to swelling and tar formation in bituminous coal may be minimized.

Hydraulic fracturing using rapid pressure release followed by water flushing of the induced fractures to help clean out the fractures ranks second to open borehole from the surface.

TABLE 2.2-7

TECHNICAL RANKING OF UCG
GASIFICATION AND LINKING METHODS

(Major classes of gasification methods are listed in order of decreasing technical viability with specific concepts under each class also ranked in order of decreasing technical viability.)

UCG CONCEPTS	PERMEABILITY ENHANCEMENT TECHNIQUE
I. Linked Vertical Well Gasification	
1. Open Horizontal Borehole from Surface	Reverse Combustion
2. Hydraulic Fracturing Using Rapid Pressure Release and Water Flushing	Reverse Combustion
3. Hydraulic Fracturing	Electrocarbonization
4. Electrolinking-Carbonization	
5. Pneumatic Fracturing	Reverse Combustion
6. Shaped Charge	Reverse Combustion
7. Hydraulic Fracturing	Chemical Comminution and Reverse Combustion
8. Shaped Charge	Electrocarbonization
9. Hydraulic Fracturing	Explosive Fracturing and Reverse Combustion
10. Shaped Charge	Hydraulic Fracturing
II. Open Borehole Gasification	
1. Reverse Flow	
2. Open Borehole From Partial Mine	Reverse Combustion
3. Coflow	
III. Blind Borehole Gasification	
1. Blind Borehole From Surface	
2. Blind Borehole From Partial Mine	
IV. Broad Front	
1. Line Drive	

Hydraulic fracturing has been used successfully for methane drainage of coal beds and the technology is continually developing. Additionally, the technique is not particularily complex or expensive and it is not generally hazardous. The main problem with this method as with other fracturing methods is the strong dependence of fracture orientation and propagation on geologic properties. If the Soviet technology of rapid pressure release is shown to provide control over fracture direction this method could become a primary technique.

2.3 RESEARCH AND DEVELOPMENT PROGRAMS AND PRELIMINARY FIELD TEST DESIGNS

2.3.1 INTRODUCTION

The Phase III section of this report describes the Research and Development programs and preliminary field tests recommended for the development of in situ gasification in thin seams of bituminous coals. The development work envisioned for the new technology is supported by an overall plan which defines the objectives, charts the path to achieve those objectives and provides overall estimated costs and schedule for the work.

The development work involves three concepts for linking vertical well gasifiers. The linking concepts developed are as follows:

- o Open borehole from the surface
- o Hydraulic fracturing
- o Electrolinking.

The R & D programs include work at both the laboratory and bench-scale level and field tests at a potential UCG site.

Costs of the R & D programs include a detailed cost breakdown for each preliminary field test.

The overall objective is to develop the UCG technology in bituminous coal to the stage where industry would accept the risk of commercial development.

2.3.2 GENERAL TOPICS

The General Topics section includes a discussion of items other than the linking concepts. Although the linking procedures are different, once the forward gasification is established and combustion is taking place in an open cavity, all UCG operations are presumed to be similiar. The concerns which effect any UCG operation not specific to a linking method are discussed. The parameters which require further study in an R & D program are identified.

Major subjects of general concern which all UCG concepts have in common were discussed.

- Linking method
- Heat losses
- Gas losses
- Product gas heating value
- Oxygen utilization
- Product gas clean-up
- Well survivability
- Resource recovery
- Subsidence.

2.3.2.1 CONCERNS SPECIFIC TO BITUMINOUS COALS

The non-swelling bituminous coals react quite differently from the swelling bituminous coals. The concerns discussed herein are directed primarily towards swelling bituminous coals. Briefly, the advantages and disadvantages of bituminous coals in their application to UCG are as follows:

- o Potential advantages

  1) Eastern bituminous coals are located near markets
  2) Thin seams should result in little or no subsidence; well survival should be less of a problem than in thicker seams
  3) Deep seams should have low water influx
  4) Socioeconomic impact in the Eastern U.S. should be minimal relative to a similiar setting in the Western U.S.
  5) Below potable water aquifers.

- o Potential disadvantages

  1) Low initial permeability
  2) Swells on heating which reduces the initial permeability
  3) Large quantities of tars and oils are produced upon pyrolysis which reduces the initial permeability and can promote override of coal seam
  4) Thin seams typical in Eastern U.S. result in high heat losses and low resource recovery
  5) Rugged terrain in certain Eastern U.S. coal fields increases complexity of site preparation and piping layout
  6) Multi-layered seams may increase the complexity and/or cost of operation.

2.3.2.2 COAL PROPERTIES RESEARCH

The R & D program addressed to the concerns specific to bituminous coal will include determining the physical and chemical properties of the coal from a specific site which has met all the requirements for development of a UCG project. The work will include laboratory and bench-scale studies on coal samples from the coring program. High priority work will include kinetic studies of the combustion process at a burning coal surface and determination of the reactivity of the coal. Math modeling will be a continuous concurrent effort during the experimental and site analysis work. Economic feasibility studies will be conducted in concert with laboratory and field work to establish meaningful targets.

The funding requirements for the laboratory and math modeling are presented in Table 2.3-1.

2.3.2.3 ECONOMIC STUDIES

A series of study cases were devised to assess the economic feasibility of UCG in bituminous coal.

The process study will involve the following:

- Field system design
- Above-ground facilities design
- Economic evaluation
- Sensitivity study for alternate coal seam depths
- Sensitivity study for alternate coal seam thicknesses
- Sensitivity study for alternate product gas composition.

Funding requirements for the economic studies are presented in Table 2.3-1.

2.3.2.4 SITE DEVELOPMENT

Prior to a UCG field test, several activities are required. A target area must be selected which possesses enough coal for

TABLE 2.3-1

COST ESTIMATE SUMMARY
LABORATORY, BENCH-SCALE, MATH MODELING AND ECONOMIC STUDIES

R & D PROGRAM	ESTIMATED COST
1. Research Program to Determine the Coal Properties Applicable to the Development of UCG in Bituminous Coal	
A. Locate Samples	$ 5,000
B. Physical and Chemical Properties	58,000
C. Kinetic Studies	110,000
D. Math Modeling	100,000
Total	$273,000
2. Process Study to Assess the Feasibility of UCG in Bituminous Coal	
A. Field System Design	$ 57,000
B. Above-ground Facilities	239,000
C. Sensitivity Study for Alternate Coal Seam Depth	25,000
D. Sensitivity Study for Alternate Coal Seam Thickness	15,000
E. Sensitivity Study for Alternate Product Gas Composition	79,000
Total	$415,000
3. Open Borehole from the Surface	
A. Locate and Procure Coal Blocks	$ 15,000
B. Tests at Atmospheric Pressure	220,000
C. Tests at Elevated Pressure	125,000
D. Math Modeling	75,000
Total	$435,000
4. Hydraulic Fracturing	
A. Physical & Chemical Properties	$ 62,500
B. Reverse Combustion Studies	129,500
C. Math Modeling	100,000
Total	$292,000
5. Electrolinking	
A. Laboratory Work	$ 28,000
B. Bench Scale Work	60,000
C. Math Modeling	200,000
Total	$288,000

commercialization of the process if the field test indicates commercialization is feasible. Once a target area is selected, a lease for coal rights must be acquired for a site within this area. Upon acquisition, the site must be characterized to determine if underground coal gasification is feasible. Prior to the field test, the site will be prepared in regards to access and security.

The following subjects relating to site development work preparatory to a field test were discussed in detail.

- Site Acquisition
- Site Characterization
- Site Preparation
- Environmental Concerns
  1) Air quality
  2) Groundwater quality
  3) Surface water quality
  4) Subsidence
  5) Bi-product disposal
  6) Socioeconomical factors
  7) Fire control
  8) Drilling waste and mud disposal
  9) Site restoration
- Post-Burn Coring and Inspection

2.3.3 OPEN BOREHOLE FROM THE SURFACE CONCEPT

This section includes a basic research program for development of an open borehole concept and a preliminary process design of facilities to accomplish a field program.

The open borehole concept requires that a directionally drilled horizontal borehole intercept the bottoms of two or more vertical wells to conduct the ignition and gasification operation. The final connection will be by air pressure and reverse combustion linking. The purpose of the reverse burn is to enlarge, stabilize and heat the borehole.

Major technical problems that have been identified with the open borehole concept are as follows:

- It may not be currently possible to control a directionally drilled borehole within ±1 foot from the bottom of a thin coal seam and intercept the bottoms of vertical wells.

- A horizontal borehole may plug, thus blocking off air flow between vertical wells.

- A borehole may not be stable over long periods. Reverse combustion may or may not result in a more stable channel.

- The overall thermal efficiency may not be as high as filtration processes, which provide for a more tortuous path.

- The sweep width of the cavity may be unacceptably reduced by the presence of an open channel.

2.3.3.1 R & D PROGRAM

The intent of the R & D program is to solve as many of the technical problems as possible by laboratory and bench-scale work. The remaining problems must be solved by field work.

The basic research proposed in this section includes laboratory tests of ignition and reverse burning in boreholes in blocks of bituminous coal which will have properties similar to the coal at the site selected for UCG development. Math modeling of the process will proceed concurrently with the basic research.

A. PROGRAM OBJECTIVES

The total R & D program specific to the use of open boreholes for UCG in bituminous coal seams has the following objectives.

- Demonstrate that a horizontal borehole can be directionally drilled from the surface to link vertical wells drilled to a typical thin bituminous coal seam.

- Develop techniques to positively connect the vertical wells and horizontal borehole and initiate combustion and forward gasification.

- Determine the accuracy of the surveying equipment which monitors the direction and location of the drill while drilling.

- Demonstrate the gasification of a bituminous coal seam at well spacings of at least 150 ft. apart.

- Determine the size and shape of the burned out cavity at different well spacings. This is directly related to resource recovery.

B. BASIC RESEARCH

The basic research is designed to accomplish the following objectives:

- o Evaluate the data from the site specific core sample analyses.

- o Develop data on reverse and forward burning in boreholes in blocks of bituminous coal.

  1) Determine the effect of hole size and gas velocity on reverse burning while using various ratios of air and oxygen enriched air.

  2) Determine the minimum temperature for reverse burn initiation.

  3) Determine the major factors which influence reverse burn velocities.

  4) Determine the change in diameter of the borehole at various reverse burn rates.

  5) Determine if the reverse burning process can be expected to stabilize the borehole.

  6) Determine the effect of feed gas composition and velocity on forward burning parameters.

- o Provide information to initiate the development of a math model for simulating reverse and forward combustion in open boreholes in bituminous coal.

A series of 14 laboratory experiments of combustion in coal blocks are described. The experiments will be conducted at atmosphere pressure. Provisions to test up to 7 atmospheres are discussed.

An estimate of the funding requirements for the open borehole basic research program is presented in Table 2.3-1.

C. FIELD TESTS

Three field tests designed to investigate the open borehole concept are presented. Shallow depth tests are not recommended because of risk of high gas losses to the surface and uncontrolled burning. It is recommended that until more definitive evidence is available field tests be limited to 300 ft. and deeper.

Briefly the field tests would be conducted in sequence as follows:

- Field Test No. 1
  The first field test would utilize a 200 foot section of the 1500 foot long horizontal borehole. Cement plugs on each end of the borehole would isolate the 200 foot section. Five vertical process wells intersecting along the horizontal borehole would be used. The major objective of Test No. 1 is to establish a fire link over a distance of 150 feet along the horizontal borehole.

- Field Test No. 2
  The second field test would utilize as much equipment as practical from the first test. Three process wells spaced at 100 feet and 200 feet intervals would be utilized. The primary objective would be to

establish a fire link over a distance of 300 feet along the horizontal borehole. A 200 foot fall back position is provided. Diagnostic and water wells would be similiar to Test No. 1. The horizontal borehole would contain cement plugs on each end of the test section for isolation purposes.

- Field Test No. 3

  The third preliminary field test would require a second horizontal borehole drilled from the surface. The second borehole would be separated from the first by 100 feet but parallel to the first in the horizontal plane. The second borehole would be drilled over a distance of 1500 feet in the horizontal plane to demonstrate directional drilling capability. The second borehole would then be plugged off at the 600 foot point and side tracked to intersect the first borehole at the 600 foot point.

  Four vertical process wells spaced at 200 foot intervals along the first borehole and three along the second borehole would be provided. The first horizontal borehole would be used for injection and the second for production.

The basic intent of the field testing program is to gradually expand the distance between vertical wells to determine the natural limitation. The third test with a slight exception is basically one side of a reverse flow concept generator as proposed by the Morgantown Energy Technology Center. It is unlikely that the actual scenario can be predicted. The learning curve from one test to the next will undoubtedly lead to unexpected problems and breakthroughs.

2.3.4 HYDRAULIC FRACTURING CONCEPT

This section proposes the investigation of hydraulic fracturing for linking vertical wells for UCG of bituminous coal. The use of methods to enlarge the initial induced fracture system such as water flushing and reverse combustion link enhancement will also be studied. Reverse combustion following hydraulic fracturing adds a complicating step to the linking operation but much of the same equipment can be used for subsequent forward gasification.

Major technical problems that have been identified with the hydraulic fracturing concept are as follows:

- The induced fracture lines may not intercept the production well and thereby not provide adequate linking.
- The coal seam may be so wet following fracturing and water flushing that ignition difficulties result.
- In a multi-well pattern, such as that associated with a commercial-scale operation, fracture lines may form and propagate in ways not permitting efficient resource utilization and controllable operations.
- The fracturing operations may fracture the roof rock and overlaying strata, resulting in possible subsequent gas losses, heavy water influx due to communication of the coal seam with overlying aquifiers and environmental problems.
- The induced fracture system may squeeze closed in the pliable bituminous coal once fracturing pressure is released even when proppants are used.

- o Flushing with water may block the fracture system instead of widening and enhancing it.

- o Air drying the fracture system may dislodge coal fines and plug the system.

The following additional technical problems may develop during a reverse combustion link enhancement:

- o Heating may cause the coal to swell and close off the fracture system.

- o Coal distillation products may fractionally condense in the fractures leading to plugging or override.

- o While a vertical fracture is directional it may lead to an override condition as communication to the top of the coal seam is almost assured.

- o While a horizontal fracture would have less tendency than a vertical one to provide communication to the top of the seam its lack of directionality would promote gas loss.

The use of the rapid release technique proposed by the Soviets should reduce the potential for pluggage by proppant and improve the chances for controlled link propagation. It may be that the use of a comminuting agent dissolved in the flush water or undiluted could enhance the fracture width better than water alone. The modified stress field concept of the French should also be evaluated.

2.3.4.1 R & D PROGRAM

The basic research proposed in this section includes physical as well as chemical tests on oriented core samples. In addition, bench scale tests involving oriented fractures of varying widths and heights are proposed. Extensive predictive modeling of various elements associated with hydraulic fracture are proposed.

A. PROGRAM OBJECTIVES

The primary objective of the hydraulic fracturing R & D program is the development of this linking method in bituminous coal as a commercially viable method of preparing a coalbed for UCG. Attendant with this objective, however, is the necessary development of our understanding of the overall UCG process.

B. BASIC RESEARCH

The basic research program for the development of the hydraulic fracturing concept is composed of three activities:

- Laboratory and bench-scale testing
- Math modeling
- Field testing

The laboratory testing on hydraulic fracturing focuses on measurement of coal and rock properties pertinent to fracturing such as: elastic moduli; fracture toughness; permeability; capillary pressure; fluid/proppant/core interactions; petrology; and filtration. These results will permit selection of the optimum fracture fluid for coal fracturing. Laboratory testing on reverse combustion involves: spontaneous ignition studies; gas permeability sensitivities; and reverse combustion simulations in varying fracture geometries under varying conditions.

Because of the site specific nature of UCG, bituminous coal samples tested in the laboratory will be taken from or near the proposed target area. A detailed site evaluation will preceed any field testing. Sites characterized as having a predominant cleat direction would enhance the probability of vertical well linking using hydraulic fracturing; however, sites with major faults and folds must be avoided with this technology.

Laboratory testing on blocks of bituminous coal will provide data on reverse and forward combustion in fracture systems. A major goal of these block studies is to determine flow rate, fracture dimensions, and blast composition which will allow forward combustion without plugging due to coal swelling and tar condensation.

The math modeling studies will take data from the laboratory program and simulate hydraulic fracturing, reverse combustion, and forward combustion models for bituminous coal. The hydraulic fracture modeling will involve: criteria for horizontal fractures; modified stress fields; pressure release; erosion of coal channels; pore pressure; diffusion; cleat tendency; and influence of fracture zones. The combustion studies will model: ignition; cavity growth; heat and mass transfer; subsidence; water influx; and visco-elastic effects.

The field testing segment of the basic research R & D program is the most important segment. Development of hydraulic fracturing of coal seams in preparation for in situ gasification is necessarily field intensive due to the nature of the process. The field studies include the following:

- Hydraulic fracturing of a single vertical well to determine the in situ stress field and major fracture direction tendency

- Linking of two vertical wells by hydraulic fracturing using water followed by water erosion and flushing of the fracture system to widen the fractures

- Air drying of a link path followed by ignition and reverse combustion

- Reproducibility testing of hydraulic fracture linking and reverse combustion

- A major field test using linked vertical wells

- Gasifier development leading up to commercialization

The funding requirements for the basic research specific to the hydraulic fracturing and the reverse combustion link concepts are presented in Table 2.3-1.

C. FIELD TESTS

Field Test No. 1

The first major field test is tentatively scheduled to be a test of the rapid pressure release concept followed by reverse combustion link enhancement. If problems with increased pressure drop through the fractured zone develop during forward gasification, one could try to refracture the coal seam and recycle to the forward gasification attempt.

Field Test No. 2

The second major field test will develop hydraulic fracture linking for UCG in a multi-well gasifier mode.

Field Test No. 3

A third major field test would focus on long term steady state operation. Additional wells would be drilled at the site to increase the total gasifier size. The goals would be to consistently produce a gas of reasonable heating value and to develop an efficient drilling, linking, ignition and gasification schedule for gasifier growth.

2.3.5 ELECTROLINKING CONCEPT

An R & D program for the development of electrolinking-carbonization in the linked vertical well concept of UCG of swelling bituminous coal seams is represented in this section. The STATE-OF-THE-ART section analyzes the present status of our knowledge of the electrolinking-carbonization process indicating what is known and what is unknown or uncertain about the process. The overall R & D program objectives and a series of auxiliary objectives are presented. These various program objectives propose research and development work aimed at providing solutions to the technical problems.

There are three major technical problems identified with the electrolinking concept as follows:

- There are no known ways of controlling the direction and dimensions of the carbonized zones which form around each electrode.
- There is a possibility that char formed from bituminous coal by electrolinking may be rigid and possess a low gas permeability. Any increase in gas flow capacity of the coal bed may be through cracks and channels which form as a result of pyrolysis. Gases which are released during in situ pyrolysis get trapped within the coal matrix and expand during the pyrolysis process causing local increases in pressure. These pressure cells can rupture forming cracks or small channels as gas bubbles are released.
- Electrical equipment is expensive, easily damaged and hazardous to operate. Power levels on the order of thousands of kilovolt-amperes are required.

Other technical problems that have been identified are:

- o Insulating the well bore from the electrode and the casing from the formation.

- o Maintaining contact between electrode and the coal seam.

- o A link override, to the coal seam roof, is favored due to the lower electrical resistances of bounding rock materials.

- o Nearby carbonized zones may cause an electrical bypass.

Laboratory and bench-scale research work will be designed to solve the technical problems identified. However, field tests will be designed to address all of the technical problems.

The following experiments are proposed to help solve the technical problems mentioned above:

- o The effect of pretreating coal with electrolyte solutions to lower the initial electrical resistance will be investigated in an attempt to control the direction of current flow between two electrodes.

- o Salts with low melting points, a high boiling point and a high electrical conductance are excellent candidates for pretreating coal samples. As power is applied, the electrolyte solution should evaporate, depositing the solid electrolyte. A few of the salts that will be tested are $Na_2CrO_4 \cdot 10H_2O$ $NaBO_2 \cdot 4H_2O$, $NaAl(SO_4) \cdot 12H_2O$ and $NaClO_4 \cdot H_2O$.

- o Dewatering specific areas to eliminate the low resistance path between the link zone and the coke zone. This should prevent short circuiting of the current through the coked zone.

- o Hydraulic fracturing prior to electrolinking as a method of placing the electrolytic solution.

- o Shaped electrodes as a method of controlling the current direction.

Electrolinking has several advantages as follows:

- o Possibility of direct well-to-well link due to the "homing" nature of the electric field.

- o Independence of the system on the swelling tendency of bituminous coal.

- o The char path between electrodes will be hot after carbonization and will self ignite upon contact with oxygen.

2.3.5.1 R & D PROGRAM

A. PROGRAM OBJECTIVES

The overall objective of the electrolinking-carbonization R & D program is the development of this linking method as an effective and reliable means of preparing a bituminous coal seam for subsequent in situ gasification. For this linking method to be effective and reliable, it should meet the following specifications:

- Provide a link path between two vertical process wells in a reasonable time and at a reasonable cost.

- The link path should permit gas flow adequate for gasification.

- The linking direction and the size and shape of the link path should be predictable and controllable.

To achieve the overall program objective, the R & D program has the following auxiliary objectives in the areas of basic research and field testing.

B. BASIC RESEARCH

The basic research program for the development of the electrolinking concept is composed of three activities:

- Laboratory and bench-scale testing
- Math modeling
- Field testing.

The laboratory testing on electrolinking involves measuring electrical properties of coal samples and conducting electrocarbonization studies on blocks of bituminous coal. The electrical properties to be measured include: specific resistance of coal and coke; electrical breakdown potentials; and AC and DC conductances.

Bench-scale studies will include evaluation of gas permeability versus power input; linking rate versus power input; continuous control of voltage versus power input; and the effect of pressure and water influx rate on linking rate. The effect of pretreating the coal with electrolyte to lower the initial resistance and focus the current flow between the electrodes will be studied.

Math modeling will simulate the data and results of the laboratory studies. Temperature, pressure, and flow profiles will be modeled.

Field testing of electrolinking will evaluate the effectiveness of using hydraulic fracturing prior to electrolinking. An electrolytic fracturing fluid will be tested to determine if the current path can be controlled.

The funding requirements for the basic research specific to electrolinking-carbonization are presented in Table 2.3-1.

C. FIELD TESTING

- Develop and perform small-scale field tests to investigate electrolinking-carbonization and subsequent forward gasification in a swelling bituminous coal bed.

- Demonstrate the reliability of electrolinking-carbonization as a vertical well linking technique in a full-scale major field test.

- Demonstrate progressive development of a multi-well gasifier by conducting a series of two-well linkings followed by forward gasification.

The R & D program emphasizes basic fundamental research devoted to fully understanding the nature of the electrolinking process and developing a means of controlling its direction in an inhomogeneous media. The next step will be a field test to evaluate the effectiveness of the control techniques.

The initial mini-test will be a two-well test with the wells spaced 100 feet apart. If the mini-test is successful, the next test will be a major field test.

Any test following the first major field test is highly speculative.

2.3.6 PRELIMINARY FIELD TEST DESIGNS

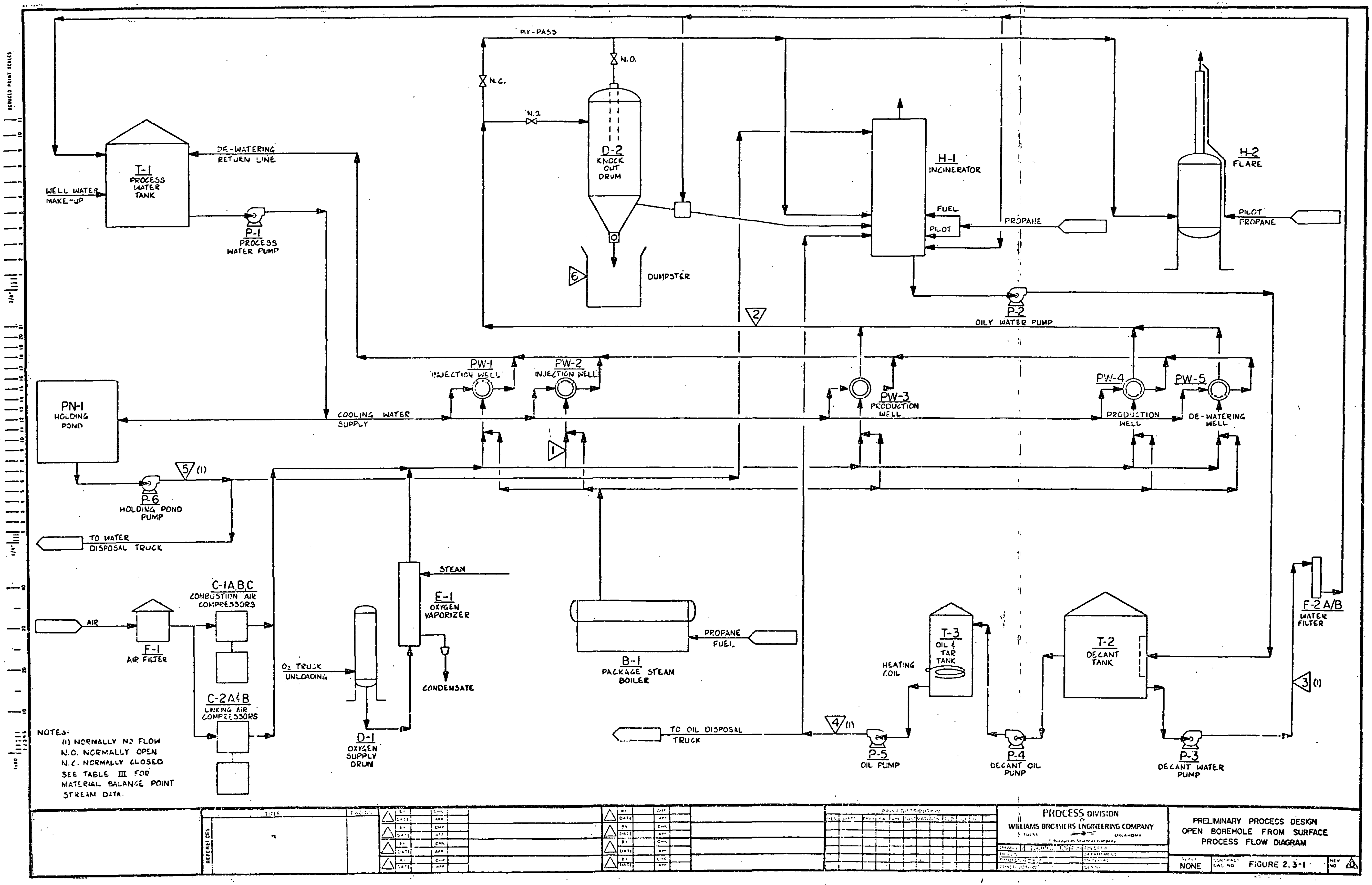
A preliminary field test design was prepared for each selected concept to determine within a ±25% accuracy the potential funding requirement. The three field test designs were sited at two different sites. The open borehole and electrolinking concepts were sited in Monroe County, Ohio where the coal is approximately four feet thick at a 460 ft. depth. The hydraulic fracture concept was sited in a deeper seam strattling Hamilton, Jefferson and Franklin counties in Illinois.

Each of the field tests is developed similarly. A specification for the field test design, a material balance, process flow diagram, equipment list, and a utility summary describe each test. An example of a process flow diagram is illustrated on Figure 2.3-1.

Based on the presumption that the individual cost elements generated on each of the preliminary field test designs would be used to estimate the costs of actual future tests, one of the tests was oxygen blown and the others air blown.

The operating parameters for forward gasification on each of the tests are as indicated in Table 2.3-2.

A summary of the funding requirements for each of the linking concept R & D programs is presented in Table 2.3-3.



BY-PASS
N.O.
N.C.
N.O.
D-2 KNOCK OUT DRUM
DUMPSTER
6
T-1 PROCESS WATER TANK
WELL WATER MAKE-UP
DE-WATERING RETURN LINE
P-1 PROCESS WATER PUMP
H-1 INCINERATOR
FUEL
PILOT
PROPANE
H-2 FLARE
PILOT PROPANE
P-2 OILY WATER PUMP
2
PW-1 INJECTION WELL
PW-2 INJECTION WELL
PW-3 PRODUCTION WELL
PW-4 PRODUCTION WELL
PW-5 DE-WATERING WELL
PN-1 HOLDING POND
COOLING WATER SUPPLY
1
5 (1)
P-6 HOLDING POND PUMP
TO WATER DISPOSAL TRUCK
AIR
F-1 AIR FILTER
C-1A,B,C COMBUSTION AIR COMPRESSORS
C-2A&B LINKING AIR COMPRESSORS
STEAM
E-1 OXYGEN VAPORIZER
O2 TRUCK UNLOADING
D-1 OXYGEN SUPPLY DRUM
CONDENSATE
B-1 PACKAGE STEAM BOILER
PROPANE FUEL
TO OIL DISPOSAL TRUCK
4 (1)
P-5 OIL PUMP
HEATING COIL
T-3 OIL & TAR TANK
P-4 DECANT OIL PUMP
T-2 DECANT TANK
P-3 DECANT WATER PUMP
F-2 A/B WATER FILTER
3 (1)
NOTES:
(1) NORMALLY NO FLOW
N.O. NORMALLY OPEN
N.C. NORMALLY CLOSED
SEE TABLE III FOR MATERIAL BALANCE POINT STREAM DATA.
PROCESS DIVISION
WILLIAMS BROTHERS ENGINEERING COMPANY
TULSA OKLAHOMA
PRELIMINARY PROCESS DESIGN
OPEN BOREHOLE FROM SURFACE
PROCESS FLOW DIAGRAM
NONE
FIGURE 2.3-1

TABLE 2.3-2

SUMMARY OF OPERATIONAL PARAMETERS
PRELIMINARY FIELD TESTS

CONCEPT	OPERATIONAL PARAMETERS: Open Borehole From The Surface	Hydraulic Fracturing	Electrolinking
Coal Consumption, Average Tons/Day	16.4	19.1	16.4
Product Gas Flow, Dry SCFM	2202	1004	2202
Thermal Production, BTU/Day (a)	253×10^6	299.6×10^6	253×10^6
Thermal Efficiency, %	48.5	63.6	48.5
Sweep Efficiency, %	65	65	65
Gas Recovery, %	95	95	95
Mols Wellhead Gas Per Mol Injected Air, Dry	1.22	2.78	1.22
Product Gas Moisture Content, Mol %	27	51.9	27
Lithostatic Head, PSI/ft.	1.0	1.0	1.0
Hydrostatic Head, PSI/ft.	0.43	0.43	0.43
Reverse Combustion Link Rate, Ft/Hr.	1	1	1.67 (b)
Link Blast Flow Rate, SCFM	252	252	252
Link Blast Composition:			
% O_2	35	35	35
% air	65	65	65
Forward Combustion Blast Rate, SCFM	1803	759	1803
Forward Combustion Blast Composition, % Air	100	--	100
Forward Combustion Feed Gas Composition, % O_2	--	50	--
Forward Combustion Feed Gas Composition, % H_2O	--	50	--
Heating Value of Produced Gas, BTU/SCF (HHV)	80	253	80

(a) Includes in situ methane
(b) Electrolinking rate

TABLE 2.3-3

COST ESTIMATE SUMMARY
OVERALL FUNDING FOR R & D PROGRAMS
AND FIELD TESTS

	CONCEPT ($000)		
R & D PROGRAMS	Open Borehole From The Surface	Hydraulic Fracturing	Electrolinking
Research Program to Determine the Coal Properties Applicable to the Development of UCG in Bituminous Coal	$ 273	$ 273	$ 273
Process Study to Assess the Feasibility of UCG in Bituminous Coal	415	415	415
Laboratory and Math Modeling Studies Applicable to Specific Concept	435	292	288
FIELD TESTS			
Site Acquisition	50	50	50
Site Characterization	168	300	168
Environmental Assessment and Impact Statement	312	303	312
Single-Well Testing	--	1,002	--
Two-Well Testing	--	259	1,230
First Major Field Test	7,006	6,069	7,220
Second Major Field Test	3,912	3,423	Indeterminate
Third Major Field Test	9,133	Indeterminate	Indeterminate
TOTAL	$21,704	$12,386	$9,956
TOTAL ROUNDED PROGRAM COST	$21.7 MM	Indeterminate	Indeterminate

2.4 CONCLUSIONS AND RECOMMENDATIONS

2.4.1 RESOURCE EVALUATION

CONCLUSIONS

- Application of UCG amenability requirements on available tonnage, seam thickness and depth and certain buffer zone criteria eliminated 17 states from the 27 states in the continental U.S. which contain identified bituminous reserves. The remaining 10 states contain a total of over 490 billion short tons of bituminous coal or 73% of the total bituminous reserve; however, only 85 billion tons have been identified in seams ≥42 inches in thickness. Of the 85 billion tons, 32 billion tons are potentially amenable to UCG. This figure represents about 4.8% of the original reserve base.

- Illinois, the state with largest deposits of identified bituminous coal, also has the largest number of attractive target areas for future UCG development.

- Evaluation of eastern bituminous seams having dips greater than 30 degrees indicated only six states - Alabama, Kentucky, North Carolina, Pennsylvania, Tennessee, and Virginia with steeply dipping bituminous reserves in seams ≥24 inches in thickness. Generally, existing data on steeply dipping bituminous seams is very sketchy due to the lack of industrial interest in such seams. Where data does exist, indications are that there is insufficient quantities of steeply dipping bituminous coal to support a commercial UCG facility in the East.

- o A marketing study of possible UCG products indicates medium BTU gas have the greatest potential economic viability.

- o One of the most logical uses for UCG product gases is for on-site electrical power generation using a co-generation or combined cycle system.

- o The marketing study also indicated the East-North-Central Census Region is the most logical section of the county to site an alternate fuels project based on UCG of bituminous coal.

- c Location of UCG facilities in the Eastern United States would have the advantage of proximity to large potential energy markets.

2.4.2 Concept Evaluation

CONCLUSIONS

- Review of the UCG literature indicates the linked vertical well concept is a technically viable gasifier arrangement for application to bituminous coal.

- Concerns specific to UCG of bituminous coals include: low native permeability; swelling tendency; tar production; low reactivity; and thin deep seams.

- Directional drilling of horizontal open boreholes from the surface for linking appears to be a technically and economically viable method. This technique offers positive control over the link size and direction; whereas, other methods are strongly dependent on native coal bed properties.

  Fracturing techniques are susceptible to increased gas losses due to overburden fracturing; whereas, directional drilling should not have this problem. An open borehole should permit initial low pressure operation and plugging due to coal swelling and tar production may be less pronounced than in fracture systems. Furthermore, directional drilling is relatively safe and does not require men underground. Directional drilling technology is continuing to advance and has been successfully used in under-river crossings, coal bed methane drainage, and offshore platform drilling.

- Reverse combustion link enhancement can be a useful addition to any concept. The technique may minimize tar formation and resultant plugging by preheating the zone prior to forward combustion. The method will widen and enhance a primary link and in most cases the same equipment can be used in the forward gasification stage.

- Application of a single linking method may not be effective in producing a stable usable link; hence, combinations of two or more methods are more viable.

- The controlled retracting injection point (CRIP) technique is a concept which should be field tested in bituminous coal.

- To improve the economic viability of concepts such as hydraulic fracturing and open borehole it may be possible, in certain seams, to drain methane prior to gasification. Other synergistic resource recovery opportunities may also be present, for example: use of the CO_2 for EOR. Or, use of hydrogen to process shale oil located adjacent to the coal seams.

- Linking concepts were ranked in order of technical viability within the context of the LVW gasifier mode. The first three concepts listed in order of decreasing rank include: horizontal open borehole from the surface (using directional drilling) followed by reverse combustion; hydraulic fracturing using the rapid pressure release method followed by water flushing, air drying, and reverse combustion; and electrocarbonization.

2.4.3 R & D PROGRAM

CONCLUSIONS

- Early UCG work in bituminous coal was performed before sufficient diagnostic equipment was available. Currently available diagnostic equipment would allow for a better evaluation of a test program.

- Additional laboratory, bench scale and field test programs are required before UCG in bituminous coal is ready for commercialization.

- The first major field test in a thin seam of bituminous coal would cost an estimated $6.2 million plus $0.2 million for an environmental impact statement. The project would extend over a 3-1/2 year period from initial site characterization to final data analysis.

- Laboratory work and math modeling studies addressed to the concerns specific to bituminous coal would cost an estimated $273,000 and would require one year to complete.

2.4.4 RECOMMENDATIONS

- Conduct an economic feasibility study to determine cost of gas produced from commercial development of UCG in bituminous coal.

- Initiate a field test program to demonstrate UCG in bituminous coal using the open borehole from the surface concept.

- Initiate a field test program to demonstrate recovery of in situ methane from UCG boreholes. The recovered methane value should reduce field development costs.

- Investigate the possible use of CO_2 recovered from UCG in thin seams of bituminous coal. Enhanced recovery of oil using CO_2 is one possiblity. The sale of CO_2 would reduce cost of UCG field program.

- Initiate a field program to develop geological and hydrological data on bituminous coal target areas selected or identified.

- Begin a program of laboratory and bench scale work to determine swelling tendency, tar formation and other properties specific to bituminous coal.

- Develop a program of math modeling in conjunction with laboratory and bench scale development work.

- The UCG technology needs to be demonstrated and the potential economic viability determined at a site in the East-North-Central U.S. which has commercially viable quantities of amenable bituminous coal before utilities/ industry will show significant interest. To bring about timely adoption of the technology, state or federal governments will need to sponsor the basic research and initial field testing.

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5.0 PHASE III - DEVELOP RESEARCH AND DEVELOPMENT PROGRAMS AND PRELIMINARY FIELD TEST DESIGNS VOLUME IV OF IV

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