

# **A Review of Underground Coal Gasification Research and Development in the United States**

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## 1 Introduction and scope

An intense and productive period of research and development on underground coal gasification (UCG) took place in the United States from the mid-1970's through the late 1980's. It began with the translation and review of Soviet literature and ended with the Rocky Mountain 1 field test. This demonstrated the feasibility of newly-developed technologies that form the basis of many UCG projects around the world today. This period began with little domestic understanding of UCG and ended with an accurate observation-based conceptual model and a corresponding predictive multi-physics mathematical model of the process. The many accomplishments of this period form the main content of this report.

This report also covers recent U.S. activities and accomplishments during the period 2004-2015, and touches briefly on the Bureau of Mines efforts between 1948 and 1963.

Most of the activities were funded by the United States Department of Energy and its predecessors. While private/commercially-funded activities are reviewed here, the emphasis is on government-funded work. It has a much greater extent of publicly available reports and papers, and they generally contain much greater technical detail.

Field tests were the marquis activities around which an integrated multi-faceted program was built. These are described in detail in Section 4. Highlights from modeling efforts are briefly covered, as the program was integrated and well-rounded, with field results informing models and *vice-versa*.

The primary goal of this report is to review what has been learned about UCG from the U.S. experience in aggregate. This includes observations, conclusions, lessons-learned, phenomena understood, and technology developed. The latter sections of this report review these things.

## 2 Overview

### 2.1 Major contributing institutions

A brief description of some of the institutions that contributed to U.S. UCG development will facilitate the overview of activities that follows.

#### 2.1.1 Bureau of Mines, AEC, ERDA, DOE

Several federal organizations in the United States had an important roll in UCG's development. Management and funding of much of the UCG program, and some of its main technical contributors resided at various times in the Bureau of Mines (BoM) (within the Department of the Interior), Atomic Energy Commission (AEC), Energy Research and Development Agency (ERDA), and finally centralized in the Department of Energy (DOE) into which many of the functions of the other institutions were rolled in 1977.

#### 2.1.2 USBM Station in Tuscaloosa, Alabama

The Bureau of Mines office in Tuscaloosa, Alabama had a technology division and experimental station that conducted the Gorgas, Alabama UCG tests in the late 1940's to late 1950's.

#### 2.1.3 MERC, METC, NETL

A government research center with expertise in coal gasification in Morgantown, West Virginia became the Bureau of Mines' Morgantown Energy Research Center (MERC), then the Morgantown Energy

Technology Center (METC) under DOE, and more recently, merged with its Pittsburgh, Pennsylvania counterpart to form the National Energy Technology Laboratory (NETL). Morgantown has always had two roles in UCG and energy research. Part of it acts as a program management arm for the Department of Energy and its predecessors in certain technical arenas including coal gasification. It has also always performed technical R&D work in coal gasification and other areas. METC looked at UCG scale-up and economics, operated the Pricetown, WV field test, and managed the UCG program.

#### **2.1.4 LERC, LETC, WRI, Universities of Wyoming and Colorado**

The Bureau of Mines Laramie Energy Research Center (LERC), in Laramie, Wyoming conducted the first and successive UCG tests at the nearby Hanna site. This was renamed to the Laramie Energy Technology Center (LET C) under DOE and then privatized in 1983 into the Western Research Institute (WRI) which remained an important part of the UCG program through the Rocky Mountain 1 test and related follow-on work.

#### **2.1.5 LLL, LLNL**

Lawrence Livermore Laboratory (LLL), renamed to Lawrence Livermore National Laboratory (LLNL) in 1982, is in Livermore, California, and is named after its founder, Earnest Lawrence. It is a very large multidisciplinary science and engineering research institution whose core mission since it began in 1952 has been in nuclear security. Livermore's original charter and its continuing nature has been innovation – pioneering new and better ways to do things. That can be seen in its series of UCG activities. Every one of Livermore's field tests was different and pioneered something new.

#### **2.1.6 Universities of Wyoming and Colorado**

Researchers at the University of Wyoming (Laramie) and the University of Colorado (Boulder) collaborated with LETC and other institutions, analyzing UCG field data and developing UCG models (c.f. Krantz and Gunn, 1983c).

#### **2.1.7 Texas institutions**

A modest amount of UCG work has been aimed at lignite fields in the state of Texas. This has mostly been funded by private industry with some state support. Organizations involved include the company Basic Resources, which operated the Tennessee Colony field test, the University of Texas at Austin, and Texas A&M University partnering with a consortium of companies. The Republic of Texas Coal Company and Mitchell Energy Corporation had planned a large-scale UCG operation (Edgar, 1983).

#### **2.1.8 Gulf Research and Development, Energy International**

The major oil company Gulf's Research and Development Company had the most active and longest-running UCG program in American private industry. On a cost-shared basis with the Department of Energy, Gulf ran the two Rawlins field tests and had a key role in the Rocky Mountain 1 test. Some of Gulf's UCG principals later joined Energy International, aimed at larger UCG projects.

#### **2.1.9 ARCO**

The major oil company ARCO had a subsidiary coal company that did UCG work including the Rocky Hill field test and made plans for larger scale operations. Some of its UCG staff had been principals in LETC's UCG program.

### 2.1.10 GRI - Gas Research Institute

The Gas Research Institute was an independent research institute in Chicago, Illinois with expertise that includes coal gasification (mainly surface) that operated on a mix of industrial and government grant funding. GRI funded some of the efforts and was a leader in the DOE-assembled consortium that ran the Rocky Mountain 1 test. More recently it merged with the Institute of Gas Technology to form the Gas Technology Institute (GTI).

### 2.1.11 Other institutions

Many other research and engineering institutions participated and made contributions to the UCG program. Many researchers at universities and research institutions conducted laboratory experiments and developed models related to UCG. Many engineering and geological service providers did much of the support work under contracts, including United Engineers for the Rocky Mountain 1 field test, and Williams Engineering for some of the earlier field tests.

## 2.2 Locations

Figure 1 shows the locations of many of the field tests and institutions involved with UCG.



Figure 1. Location of U.S. UCG institutions and field tests. (LLNL & Ergo Exergy)

## 2.3 Periods of UCG activities

### 2.3.1 Pre-1970 work

While there must have been some awareness of UCG by coal gasification interests in mid-twentieth century America, growing oil, gas, and mined coal infrastructure provided plenty of energy at low costs. There was little to no motive for a government or corporate UCG program. The only significant work

before 1970 seems to be by the U.S. Bureau of Mines at Gorgas, Alabama, beginning in the late 1940's. Little from this project carried forward into the 1970's program consciousness besides the fact of a field test.

### 2.3.2 The main 1970's-1980's program and activities

United States government institutions (see Section 2.1) initiated UCG research in the early 1970's, and grew it into a well-funded, sustained, and technically vibrant program. The primary motivation was to advance the domestic energy security of the United States. Oil and gas supplies were appearing limited, the OPEC oil embargo was to hit soon, and U.S. coal resources were and still are enormous. Converting plentiful domestic coal into gas fuels for power or conversion to liquid fuels was an appealing goal. Secondary considerations included the opportunity to reduce deaths from underground mining and the environmental impacts of open pit mining.

Throughout its course, the long-term objective was large-scale commercial operations that would have a significant impact on U.S. energy supplies. The program began with paper studies, creation of large-scale conceptual design schemes. An important early activity in the program was the translation and study of Soviet reports on UCG, thus taking advantage of the greatest previous efforts in UCG technology development. This guided early program thinking and approaches, underpinning the early Hanna tests and much of LLL's early thinking.

The U.S. approach was a multi-faceted program that included modest-scale field tests, large-scale conceptual designs, scientific understanding and modeling, some focused laboratory experiments, and technology innovation. Concepts began by emulating the understanding of Soviet technical approaches, and evolved into U.S.-developed methods and technologies. Great progress was made in understanding and modeling the process, development of designs and operations that held promise for efficient operations and scale-up, training and experience of a research, development, and operations workforce, and experience with the difficult challenge of groundwater contamination. The program largely ended after the capstone field test, Rocky Mountain 1, in which a DOE-led consortium of public and private organization successfully executed the largest American field test using the best methods that had been developed.

By the late 1980's and early 1990's American UCG activities tailed off to only a bit of Rocky Mountain 1 technical follow-up and report-writing, and some groundwater remediation activities. Oil and gas prices had stabilized and the U.S. Government philosophy of energy technology development had shifted towards the private sector. Over the next two and three decades, the individuals who developed UCG expertise moved to other work, retired, and/or passed on.

### 2.3.3 A small revival in 2004-2015

Growing UCG interest and activities around the world in the early 2000's combined with increasing and more variable gas prices rekindled U.S. activities from the mid 2000's to the mid 2010's. International UCG technology companies, owners of potentially suitable coal resources, and project developers worked to position themselves for and initiate ambitious UCG projects in many U.S. states. A few major energy companies became informed about UCG technology and considered U.S. project possibilities. Some federal and state government agencies, universities, and NGO's (nongovernmental organizations) took an interest in and studied UCG to various degrees during this period. Wyoming supported a UCG review and detailed study of a notional large project and its costs (GasTech, 2007). The Clean Air Task Force supported early work by LLNL during this period. The Indiana Geological Survey and Purdue University evaluated the suitability of Indiana coal resources for UCG. (Shafirovich et al., 2009). The U.S. Department of Interior, Office of Surface Mining, Restoration, and Enforcement organized regulators

from several states and Native American nations to become better versed in UCG and collectively wrestle with permitting processes and issues. Wyoming regulators proceeded furthest down the permitting path with one pilot test proposed by a UCG company.

Lawrence Livermore National Laboratory revived a modest UCG program at the beginning of this period, motivated largely by the goal of reducing coal's carbon footprint (c.f. Friedmann, 2005). It seemed possible that UCG had the potential to provide energy from plentiful coal at the price and carbon footprint of natural gas. Surface gasification of coal was technically amenable to efficient separation of not only conventional air pollutants but also of CO<sub>2</sub> that could then be sequestered. Available cost estimates for UCG were lower than for either natural gas at the time or surface gasification. It seemed the costs savings from cheap UCG could be applied to carbon capture and sequestration (CCS) without much of a net increase in energy cost. Especially for locations in the world with indigenous coal, high energy prices and energy security issues, UCG seemed to offer the possibility of fueling energy needs while sequestering the carbon affordably. The program's technical work ended up emphasizing development of process models, evaluation of resources for UCG suitability, UCG technical education and training, geophysical monitoring, reducing greenhouse gas emissions, and groundwater contamination. Following support for LLNL's initial Best Practices review, the DOE did not provide programmatic support, largely because of its assessment of UCG's groundwater contamination risks.

Interest and activities in UCG and coal diminished in the latter years of this period with plentiful oil and gas production from fracturing operations and greater weighting of the impacts from greenhouse gas emissions.

### 3 Key references

The following references are recommended for the “top shelf” of both the serious newcomer to UCG and the working professional. They go a level deeper and broader than this report, and offer perspectives from multiple authors.

#### 3.1 Recent broad reviews and collections

Several recent reviews and collections of information provide accessible entry-points and convenient desktop references on the U.S. work in UCG. Many of these reports were motivated by the need for the new UCG community to re-learn what was known by the 1970's-1980's generation.

Couch (2009) authored for the IEA Clean Coal Centre an excellent and extensive wide-scope review of UCG that includes a generous portion devoted to U.S. results and contributions. The report is both descriptive and thoughtful and should be on every UCG workers shelf.

Shafirovich (2011) is a very convenient and useful “desktop reference” for conveniently finding field test details. It is an extensive compilation of information from all the DOE-sponsored UCG field tests of the 1970's and 1980's, from Hanna 1 to Rocky Mountain 1. Largely comprised of excerpts from original reports, information for most field tests include site description and geology, well plan, instrumentation, an event timeline, gas injection and product history, cavity growth history, summary test statistics, environmental monitoring, and lessons learned.

Singer et al. (2012) is also useful as a “desktop reference” for the geometry of UCG cavities. They compiled and analyzed sketches of the final cavity geometry for many of the field tests, as well as summary test information.

LLNL's 2000's program began in 2004, then produced the well-known critical review of UCG titled "Best Practices in Underground Coal Gasification" (Burton et al., 2008). This reviews UCG technology, tabulates U.S., Soviet, and other international field tests, summarizes much of LLNL's work, provides an insightful geologic framework, and addresses the prevention of groundwater contamination. This distills from U.S., Soviet, European, and Australian experiences to arrive at several lessons learned and suggestions for best practices. While this was written at the beginning of the new program, much of it is valid and thoughtful.

Two recent journal articles reviewing UCG include some coverage of U.S. work. Shafirovich and Varma (2009) provide qualitative descriptions of UCG, list some site selection parameters, and devote two pages to U.S. field-test and modeling work of the 1970's and 1980's. Bhutto et al. (2013) reproduce various qualitative descriptions and sketches of UCG from past decades, provide much detail on chemistry and transport fundamentals, and review process models.

A large fraction of the technical communication about UCG in the recent past, including U.S. work, has been in the presentations and proceedings of conferences. Proceedings from the following recurring conferences are recommended references. Proceedings from the Conferences, Workshops, and Courses organized by the UCG Partnership/Association; IEA Clean Coal Centre UCG Workshops; and the annual Pittsburgh International Coal Conference.

### **3.2 1970's and 1980's broad reviews and collections**

The following reviews and collections of information from this generation provide accessible entry-points and convenient desktop references on the U.S. work in UCG.

An exceptionally complete chronicle of U.S. UCG activities is provided in the annual Proceedings of the (2<sup>nd</sup> through 14<sup>th</sup>) Annual Underground Coal Gasification Symposia (1976-1988), followed by the Proceedings of the International UCG Symposium (1989, ...). Preparation of written papers on accomplishments was an obligation of most DOE-funded programs. Participant papers from industry, academia, and sometimes international organizations are also well-represented, as this was the one main UCG conference of its time.

LLNL's final program report (Thorsness and Britten, 1989) contains a concise summary of eighteen years of UCG work by Livermore. It emphasizes the field tests and highlights LLNL's major accomplishments and "firsts." It summarizes what has been learned about UCG and what remains to be learned. It lists 200 of Livermore's far more numerous reports on UCG from 1972 through 1989.

Dockter (1986) presents a brief introduction to UCG and briefly summarizes the major field test programs from Gorgas in 1946 through Centralia in 1983.

Stephens et al. (1985) gives a brief overview of UCG including its chemistry, methods of linking, and the CRIP process. By this time in the program a fairly-accurate qualitative understanding of UCG phenomena had been developed and is described. DOE-funded, privately-funded, and international tests and programs are summarized briefly. LLNL's recent field test at Centralia, in which the feasibility of CRIP was first proven, is also described in some detail. Short sections address environmental considerations and costs.

Krantz and Gunn's "State of the Art" volume (1983a) is a collection of well-written review papers on selected topics that were presented at the 1982 AIChE Spring meeting. It provides a snapshot of UCG understanding, progress, and challenges at that time. It contains a concise summary of all the Hanna tests, and a description of ARCO's Rocky Hill test.

Another mid-program review is Stephens, et al. (1982). It briefly reviews the field test programs to date. Notably, this includes privately-funded tests, described in a bit more detail than in the Stephens et al. (1985). Key general observations and conclusions about UCG are summarized.

Cena and Thorsness (1981) created and populated a very detailed computer database for all DOE-funded UCG field tests through 1979, including all the Hanna and Hoe Creek tests, Pricetown I, and Rawlins I. The cited report on the database “results” is an extremely useful reference for these tests. In addition to describing the database, the report gives for each test a general description, chronology, description of the data available, and well layout. The report then presents summary tables and time-history plots for the various important time periods of each field test. The data include the entire time histories of stream temperatures, pressures, flow rates, and compositions, as well as information required to complete a heat balance and elemental and species balances. Different authors from different institutions at different times often used different units and bases for reporting the compositions, mass balances, and efficiency results from their tests. Cena and Thorsness took pains to convert all the data to consistent units using consistent bases, and they analyzed them using consistent assumptions. The underlying database, if still accessible, would be useful for technical specialists needing to dive deep into the data, for example to inform or validate a process model. It is unfortunate that the published database “results” end with Rawlins I. However, Cena and Thorsness continued to analyze subsequent LLNL test data by the same methods to produce results published in topical reports on individual tests.

Two early full-scope reviews came near the beginning of the main U.S. program, before so much had been done and learned. Gregg and Edgar’s (1978) review article in the AIChE Journal is a very technical description of UCG that illustrates American understanding of the process at that time. It covers in considerable detail what had been learned from translations of Soviet literature about UCG phenomena, practice, and scale-up schemes. UCG phenomena are described and there is a detailed section on chemistry. While several of the sketches portray well the complexity of UCG, many of the technical reaction engineering models of the process are quite idealized. An extensive reference list emphasizes Soviet work and theoretical modeling work.

An early comprehensive monograph by Lamb (1977) captures early program thinking and provides much useful information on UCG work before the mid 1970’s. It reviews UCG history, technology, and the current work and plans at that time. It emphasizes U.S. work, but also covers international historic efforts. A strength of this monograph may be in the presentation of a very wide variety of operational concepts, including many mine-based concepts, and early large-scale conceptual “mine-plan” sketches. Those believing they have conceived of a new operating approach or gas-chemistry manipulation trick might be disappointed to find it already reviewed in this 1977 book. More than enough coal gasification chemistry is presented. The descriptions of development programs, and large-scale plans show an early-program optimistic naivety.

### 3.3 Single-topic summary reports

LERC’s Hanna series of field tests were summarized well in one paper by Bartke and Gunn (1983). ARCO’s Rocky Hill test is described well by Bell et al. (1983). A good summary report that covers both of Gulf’s Rawlins tests is Bartke (1985), which also includes a comprehensive bibliography of Rawlins and steeply-dipping bed work.

LLL’s Hoe Creek series of field tests and their results were described in detail by Stephens (1981), and more briefly by Thorsness and Creighton (1983) who then analyze and effectively explain the results from select periods of operation using an energy balance construct. LLL’s series of Large Block tests at Centralia were summarized by Hill and Thorsness (1983), and their Partial Seam CRIP Test there was

summarized by Cena et al. (1984) or, highly overlapping and written a few months earlier, Hill et al. (1984b).

The only full-scope, relatively short summaries of the Rocky Mountain 1 (RM1) test appear to be in the recent reviews listed above, plus a brief final report by Dennis (2006). Contemporary descriptions of specific aspects of the Rocky Mountain 1 (RM1) test appear in the Proceedings of the 13<sup>th</sup> and 14<sup>th</sup> Annual UCG Symposium (1987 and 1988), with the former emphasizing site description and plans, and the latter emphasizing results and analyses. A chronology and description of results is found in Bloomstran et al. (1988). Cena et al. (1988a and 1988b) review both the ELW and CRIP modules of RM1, and analyze and interpret results. Thorsness et al. (1988) describe the CRIP module briefly, detail the CRIP process, and analyze results. Boysen, et al. (1988) described the post-burn “Clean Cavern” operations of post-burn venting, flushing, and cooling, with results reported later (Boysen et al., 1990). Maps of the ELW and CRIP module cavities based on post-burn coring are found in Lindblom et al. (1990) and Oliver et al. (1991). Groundwater evaluation of RM1 was reported in Lindblom and Smith (1993).

Two references serve the dual purpose of describing LLNL’s conceptual understanding of UCG and its important phenomena, and their mathematical models of UCG that distill the essence of these phenomena into something calculable. Britten and Thorsness (1989) describe their 2-D model of cavity growth and product composition for a single-cavity UCG forward burn (CAVSIM). This includes the essential chemistry, heat transfer, gas transport, water permeation, spalling of coal and overburden, rubble accumulation within the cavity, and exit-link chemistry and condensation. Camp et al.’s (2013) description of LLNL’s modern-era flexible-geometry 3-D UCG simulator provides illustrations and notes that describe in qualitative terms these same phenomena that the earlier LLNL team and others discerned to be important (plus improved fluid and thermal interactions with the surroundings).

An outstanding report on Rocky Mountain 1’s Clean Cavern Concept and results (Boysen et al., 1990) also serves as a review of research and understanding related to groundwater contamination at the end of the main U.S. program in UCG, and has an extensive bibliography. By the late 1980’s a large fraction of the U.S. UCG efforts and technical reports were directed at UCG’s issue of groundwater contamination. The Proceedings of the Fourteenth Annual UCG Symposium (1988) contains a snapshot of this work at RM1, Hanna, and east Texas. The UCG and regulatory agency report literature of the years following is full of detailed reports on contaminant chemistry, groundwater analyses, and the progress of remediation and monitoring activities. A recent report on ground water contamination covers many of the environmental lessons-learned from the U.S. field tests, and describes qualitatively the chemistry and transport phenomena involved, possible vectors and scenarios for contaminant spread, and mitigation strategies (Camp and White, 2015).

## 4 Field tests

### 4.1 Summary

Table 1 provides summary information on UCG field tests conducted in the United States between 1948 and 1988.

**Table 1. Summary of UCG field tests in the United States**

#### Early Hanna

Test name	Hanna I-hyd.frac	Hanna I-main	Hanna II Phase IA	Hanna II Phase IB	Hanna II Phase II	Hanna II Phase III
<b>Dates</b>	3/73 - 5/73	5/73 - 3/74	5/75 - 7/75	7/75 - 8/75	'12/75 - 5/76	5/76-7/76
<b>Operator</b>	LERC	LERC	LERC	LERC	LERC	LERC
<b>Location</b>	Hanna, WY	Hanna, WY	Hanna, WY	Hanna, WY	Hanna, WY	Hanna, WY
<b>Basin</b>	Hanna	Hanna	Hanna	Hanna	Hanna	Hanna
<b>Coal</b>						
<b>Consumed (Mg)</b>	818	4,347	1,650	769 + RB	4,311	4,641
<b>Rank</b>	HV Bit. C Not swell/agglom	HV Bit. C Not swell/agglom	HV Bit. C Not swell/agglom	HV Bit. C Not swell/agglom	HV Bit. C Not swell/agglom	HV Bit. C Not swell/agglom
<b>Htg. Value (kJ/kg)</b>	20,000	20,000	20,000	20,000	20,000	20,000
<b>Thickness (m)</b>	8.8	Top ~5 of 8.8	9.1	9.1	9.1	9.1
<b>Depth (m)</b>	114	114	84	84	84	84
<b>Dip (degrees)</b>	7	7	7	7	7	7
<b>Process</b>						
<b>Injectant</b>	air	air	air	air	air	air
<b>Link method</b>	Hydraul. Fractur	Reverse Burn	Reverse Burn	Reverse Burn	Reverse Burn	Reverse Burn
<b>Inj-Prod Spacing (m)</b>	9 & 18	18	18	18	18	18
<b>Design &amp; Operations</b>	Ignit. & inject'n into a central well. Prod'n from multiple surrounding wells	5 vertical inj/prod wells. RB links between many pairs of these. Forward burns between combinations of wells.	Simple 2 vertical wells linked by reverse burn, followed by forward burn.	RB linked from the HII-1A cavity to a new 3rd vert. well. Forward burn injecting into the new well.	Simple 2 vertical wells linked by reverse burn, followed by forward burn.	Tried to create a broad link between one link and a parallel burn cavity (failed). Did simple 2-well forward burn.
<b>Results</b>						
<b>Days of Ign. &amp; R.B.</b>	1	128	14	11	45	16
<b>Days Fwd (air / ox-st)</b>	60	168	37	37	27	45
<b>Consumed Fwd. (Mg)</b>	818	3,304	1,620	769	3,680	4,258
<b>Gas HV Fwd (MJ/Nm<sup>3</sup>)</b>	4.2	5.0	5.5	5.7	6.8	5.5
<b>Gas Recov Fwd (%)</b>	14	103	78	129	99	100
<b>Highlights, Accomplishments, Observations, Comments, Problems, Conclusions</b>	Hydraulic fracturing with sand proppant is not an adequate link. High gas leakage through open boreholes and casing failures.	First successful UCG test of this era! RB linking between many wells and burn cavities showed scale-up potential.	Did simple 2-well test that worked well	Repeated scale-up technique of linking from a mature cavity to a new well, and injecting into the new well.	Did another similar test that worked pretty well	Attempted broad front advancement between links and cavities in both reverse and forward modes. Both failed.

### Later Hanna, Rocky Hill, and Pricetown

Test name	Hanna III	Hanna IV-A	Hanna IV-B	Rocky Hill	Pricetown I
<b>Dates</b>	6/77-7/77	12/77-6/78	4/79-9/79	9/78 - 11/78	6/79-10/79
<b>Operator</b>	LERC	LERC	LET C	ARCO (LET C heritage)	METC
<b>Location</b>	Hanna, WY	Hanna, WY	Hanna, WY	Reno Junction, WY	Pricetown, WV
<b>Basin</b>	Hanna	Hanna	Hanna	Powder River	Pittsburg seam
<b>Coal</b>					
<b>Consumed (Mg)</b>	4,771	5,036	2,042	3,270 + RB	885
<b>Rank</b>	HV Bit. C Not swell/agglom	HV Bit. C Not swell/agglom	HV Bit. C Not swell/agglom	Subbit. C	HV Bit. A Swelling & agglom
<b>Htg. Value (kJ/kg)</b>	20,000	20,000	20,000	20,800	high
<b>Thickness (m)</b>	9.7	8.5	8.5	top 20 of 30	1.8
<b>Depth (m)</b>	50	98	98	190	270
<b>Dip (degrees)</b>	7	7	7	low	low
<b>Process</b>					
<b>Injectant</b>	air	air	air	air	air
<b>Link method</b>	Reverse Burn	Reverse Burn	Reverse Burn	Reverse Burn	Reverse Burn
<b>Inj-Prod Spacing (m)</b>	18	31	23	23	18
<b>Design &amp; Operations</b>	Simple 2 vertical wells linked by reverse burn, followed by forward burn.	Multiple vert inj/prod wells attempted to link by RB. Forward burns attempted between various well combinations.	Multiple vert. inj/prod wells attempted to link by RB. Forward burns attempted between various well combinations.	3 vert inj/prod wells in a line linked by RB. Forward burn injected into an end well and produced from the middle well.	3 vertl inj/prod wells in a line linked by RB; cycled to open links. Fwd burn injected into an end well and produced from the middle well.
<b>Results</b>					
<b>Days of Ign. &amp; R.B.</b>	16	107	83	10	106
<b>Days Fwd (air / ox-st)</b>	38	58 / -	23	60	12
<b>Consumed Fwd. (Mg)</b>	4,734	4,550	1,334	3,270	450
<b>Gas HV Fwd (MJ/Nm<sup>3</sup>)</b>	5.5	4.1	5.4	7.40	6.9
<b>Gas Recov Fwd (%)</b>	92	80	92		114
<b>Highlights, Accomplishments, Observations, Comments, Problems, Conclusions</b>	Extensive groundwater monitoring, but no results reported	Seemed like another similar test, but there were many problems.	Seemed like another similar test, but there were many problems.	Replicated Hanna-METC methods in a thicker deeper seam of different coal.  Monitored overburden subsidence and hydrology affects	Only U.S. test in swelling agglom. coal.  RB links created but difficult & high resistance.  Persistent plugging in rev. & fwd modes.

**Hoe Creek and Rawlins**

Test name	Hoe Creek I	Hoe Creek II	Hoe Creek III	Rawlins I	Rawlins II
<b>Dates</b>	10/76-'10/76	10/77-12/77	8/79-10/79	10/79'12/79	8/81-11/81
<b>Operator</b>	LLL	LLL	LLL	Gulf	Gulf
<b>Location</b>	Gillette, WY	Gillette, WY	Gillette, WY	Rawlins, WY	Rawlins, WY
<b>Basin</b>	Powder River	Powder River	Powder River	Hanna	Hanna
<b>Coal</b>					
<b>Consumed (Mg)</b>	190	2,658	4,036	1,513	7,770 + RB
<b>Rank</b>	Subbit.	Subbit.	Subbit.	Subbit. B	Subbit. B
<b>Htg. Value (kJ/kg)</b>	18,960	18,960	18,960	23,550	23,550
<b>Thickness (m)</b>	7.6/5/3.4	7.6/4.6/3.4	7.6/5.4/3.0	11.4	11.4
<b>Depth (m)</b>	~40m to F2	38 to F2	54 to F2	113	155
<b>Dip (degrees)</b>	low	low	low	63	63
<b>Process</b>					
<b>Injectant</b>	air / -	air / oxy-stm	air / oxy-stm	air / oxy-stm	oxy-stm
<b>Link method</b>	Explosive Fracturing	Reverse Burn	Borehole + RB expand	Reverse Burn	Borehole + RB Links
<b>Inj-Prod Spacing (m)</b>	10	18	30.5 & 41	18	60
<b>Design &amp; Operations</b>	High explosive fractured between 2 vertical process wells. Fwd burn between them.	Simple 2 vertical wells linked by reverse burn, followed by forward burn.	Horizontal borehole link between 3 vertical wells. Expanded by RB. Fwd burn at 30m space, extended out to 41m.	Steeply dipping bed. Directionally-drilled injection and production wells. Injection point 18 meters down-dip from production point. RB link.	One vertical production borehole between two injection wells. Injected into each well separately and into both together.
<b>Results</b>					
<b>Days of Ign. &amp; R.B.</b>	1	14	3	7	~30
<b>Days Fwd (air / ox-st)</b>	11 / -	56 / 2	7 / 47	28 / 5	- / 65
<b>Consumed Fwd. (Mg)</b>	190 / -	2,470 / 55	334 / 3,655	1,225 / 228	- / 7,767
<b>Gas HV Fwd (MJ/Nm<sup>3</sup>)</b>	4.0 / -	4.3 / 10.5	4.5 / 8.4	6.0 / 8.4	- / 12.8
<b>Gas Recov Fwd (%)</b>	93	78	83	97	
<b>Highlights, Accomplishments, Observations, Comments, Problems, Conclusions</b>	First explosively-fractured rubble bed trial in program. Successful but sub-optimal and hard to control pattern.	First oxygen-steam UCG in program. Inj. well broke near top causing heat loss to wet roof rock	First horizontal borehole link and borehole ELW in program. UCG "burns" through a 5-m interburden to reach the next seam.	First successful U.S. test in steeply dipping bed. Used directionally drilled boreholes.	Challenges the second time. RB links between boreholes and cavities don't go where expected. Gasified lots of coal but not easy.

**Centralia and Rocky Mountain I**

Test name	Centralia Large Block LBK5,2,3,4	Centralia Large Block LBK1	Centralia PS-CRIP	Rocky Mountain I- ELW	Rocky Mountain I- CRIP
<b>Dates</b>	11/81-1/82	1/82	10/83-11/83	11/87-1/88	11/87-2/88
<b>Operator</b>	LLL	LLL	LLNL	GRI Consortium	GRI Consortium
<b>Location</b>	Centralia, WA	Centralia, WA	Centralia, WA	Hanna, WY	Hanna, WY
<b>Basin</b>	Tono	Tono	Tono	Hanna	Hanna
<b>Coal</b>					
<b>Consumed (Mg)</b>	25x4	30	2,400	4,000	10,200
<b>Rank</b>	Subbit.	Subbit.	Subbit.	HV Bit. C	HV Bit. C
<b>Htg. Value (kJ/kg)</b>				20,000	20,000
<b>Thickness (m)</b>	top 7.6 of 11	top 2 of 11	top 6 of 11	top 5 of 9	top 7 of 9
<b>Depth (m)</b>	16	16		112	108
<b>Dip (degrees)</b>	15	15	14	7	7
<b>Process</b>					
<b>Injectant</b>	- / oxy-stm	- / oxy-stm	- / oxy-stm	- / oxy-stm	- / oxy-stm
<b>Link method</b>	Borehole	Borehole	Borehole	Borehole	Borehole
<b>Inj-Prod Spacing (m)</b>	18	11 then 18	22 then 22 then 15	90	90
<b>Design &amp; Operations</b>		Linear CRIP	Parallel CRIP w vertical initial production well. (1 H Inj well & borehole link. 1H Prod well & borehole link. 1 V initial prodn well.)	Horizontal production well & borehole link to 2 vertical inj. wells. Fwd burn fr distal well. ELW switch to 2nd well failed	
<b>Results</b>					
<b>Days of Ign. &amp; R.B.</b>	1	1	1	4	4
<b>Days Fwd (air / ox-st)</b>	- / 3-6 ea	- / 4	- / 30	7 / 40	3 / 90
<b>Consumed Fwd. (Mg)</b>	- / ~25 ea	- / 30	- / 2,400	4,000 total	10,200 total
<b>Gas HV Fwd (MJ/Nm<sup>3</sup>)</b>	- / 10.7	- / 10.8	- / 9.2	- / 10.3	- / 11.3
<b>Gas Recov Fwd (%)</b>	21-61	85	83	91	89
<b>Highlights, Accomplishments, Observations, Comments, Problems, Conclusions</b>	Horizontal injection wells.  Excavation of cavities informed rubble-filled nature, even in early all-coal stages.	First CRIP maneuver in the field was successful.  First "Linear CRIP" field test.  Excavation of young cavity	Second CRIP maneuver in the field.  First "Parallel CRIP" field test.  Post-burn excavation of full-sized cavity.	Clean Cavern Concept minimized groundwater contamination.  Inject. well completion at top of seam gave poor performance.	First demonstration of multiple CRIP maneuvers. "Parallel CRIP". CRIP successfully rejuvenate burn  Clean Cavern minimized contamination

**Centralia and Rocky Mountain I**

Test name	Gorgas series	Fairfield ?"Big Brown"	Tennessee Colony	Alcoa	Carbon County
<b>Dates</b>	1948-59	1976	1978-79	1980	1995
<b>Operator</b>	USBM	Basic Resources	Basic Resources	Texas A&M Consort.	Williams
<b>Location</b>	Gorgas, AL	Fairfield, TX	Tenn. Colony, TX	Alcoa, TX	Rawlins, WY Hanna
<b>Basin</b>					
<b>Coal</b>					
<b>Consumed (Mg)</b>	215 in 1st test		4,100	small	
<b>Rank</b>	HV Bit. A	Lignite	Lignite	Lignite	Subbit.
<b>Htg. Value (kJ/kg)</b>					~=Rawlins
<b>Thickness (m)</b>	1		2.2	4.5	~=Rawlins
<b>Depth (m)</b>	9				>Rawlins
<b>Dip (degrees)</b>	flat				steep
<b>Process</b>					
<b>Injectant</b>	air; maybe ox-st	air	air / oxy-stm	air	
<b>Link method</b>	R. Brn, Hyd.Frac.?			Reverse Burn	
<b>Inj-Prod Spacing (m)</b>				9	
<b>Design &amp; Operations</b>	"Soviet methods." Incl. mine addits, RB links, possibly hydraulic fracturing	"Soviet"	"Soviet"		
<b>Results</b>					
<b>Days of Ign. &amp; R.B.</b>				all	
<b>Days Fwd (air / ox-st)</b>		26	197 total	0	
<b>Consumed Fwd. (Mg)</b>			4,100 total	0	
<b>Gas HV Fwd (MJ/Nm<sup>3</sup>)</b>	2 <sup>+</sup> / 5 <sup>-</sup> fr. 1st test	4.7	3.0 / 8.6	1.3-5.6 when linking	
<b>Gas Recov Fwd (%)</b>	low				
<b>Highlights, Accomplishments, Observations, Comments, Problems, Conclusions</b>	First U.S. field tests.  High gas losses.  Roof collapse.	26-day trial	Heat loss to overburden; high water intrusion rates	21-days of unsuccessful RB linking. Mech failure of well casings.	Unsuccessful short operation  Groundwater contamination from high operating pressures

**Table Definitions**

Test name	Parameter definitions
<b>Dates</b>	Date range from first ignition to termination of oxidant injection.
<b>Operator</b>	Institution in charge of the test
<b>Location</b>	City, State in U.S.
<b>Basin</b>	Geological basin
<b>Coal</b>	
<b>Consumed (Mg)</b>	Total coal consumed (Mg) for all phases of the entire field test (gas loss corrected and including char)
<b>Rank</b>	Coal rank
<b>Htg. Value (kJ/kg)</b>	Coal higher heating value, as received (kJ/kg)
<b>Thickness (m)</b>	True seam thickness. "top" used the upper part. For two seams, thicknesses are bottom\interburden\top.
<b>Depth (m)</b>	Vertical depth from the surface to the top of the seam at the main cavity or injection point (m)
<b>Dip (degrees)</b>	Seam dip, degrees
<b>Process</b>	
<b>Injectant</b>	Injection gas composition: air, mixtures of oxygen and steam, or separate periods of each.
<b>Link method</b>	Main method of creating a permeable path between injection and production well(s).
<b>Inj-Prod Spacing (m)</b>	Distance between cased injection points and cased production points
<b>Design &amp; Operations</b>	Description of design and operations, including process wells, linking, forward burn injection and production wells, switching injection points, etc.
<b>Results</b>	
<b>Days of Ign. &amp; R.B.</b>	Number of days for ignition, reverse burn linking and connecting, and link enhancement operations
<b>Days Fwd (air / ox-st)</b>	Number of days of main forward burn operation
<b>Consumed Fwd. (Mg)</b>	Coal consumed during the main forward burn periods (gas loss corrected and including char). (air / oxy-st)
<b>Gas HV Fwd (MJ/Nm<sup>3</sup>)</b>	Average higher heating value of dry product gas during forward burn phases. (air / oxy-st)
<b>Gas Recov Fwd (%)</b>	Estimated percent of gas that is recovered through the production well during forward burns (1 minus loss)
<b>Highlights, Accomplishments, Observations, Comments, Problems, Conclusions</b>	Highlights, accomplishments, observations, comments, problems, conclusions

Product gas composition varied widely between tests. A table of average compositions is in Section 7.10.

In the first several field tests, several U.S. institutions developed competency in the Soviet-developed approach in which reverse burns are used to link vertical wells, with the main “forward-burn” phase of gasification taking place by injecting air into one of those wells or a sequence of them. Oxygen-steam injection was tried successfully and over time became the preferred injectant. The Soviet scheme for gasifying steeply dipping beds was tried successfully. The later tests in the series began to take advantage of the newly emerging and improving technology of directional drilling to create in-seam links between injection and production points.

Throughout the series, the R&D nature of the program advanced the understanding of the UCG process and its interactions with the environment. This included a growing awareness of problems with groundwater contamination and improved understanding of how to minimize it. Experience, understanding, and innovation led to the invention of the CRIP process. By the last field test, U.S. practice and preferences had swung solidly toward using directionally drilled borehole links, with a leaning toward CRIP over ELW. It was expected that deeper projects would be favored because of better isolation of contamination risks from the surface.

The final Rocky Mountain 1 test had two modules, both of which used horizontal boreholes for linking. One was used the Extended Linked Well (ELW) method, described below. This method might have the best economic potential for relatively shallow seams in which many vertical wells could be afforded. The second module used the newly-invented CRIP method, described below. This method appears to have the best economic potential for relatively deep seams for which having fewer longer wells may be more cost effective. The ELW module performance was handicapped by incorrect location of the well completions. The CRIP module performance was excellent. Improved practices for minimizing groundwater contamination were used with good success.

The major field tests are covered below, roughly organized by chronology and site/operator. The emphasis is on what was tried and what was learned to advance UCG understanding, capabilities, and technology. More details can be found in the references provided. The order of presentation, like the story, goes from old to new. The early tests are described briefly because they represent evolution along the learning curve. More detail is provided for the later tests because they describe what the program evolved to, given what was learned earlier. The RM1-CRIP description is presented in much more detail than the rest, because it embodies much of what the U.S. had learned along the way.

## 4.2 The Hanna Series of Field Tests (LETc)

### 4.2.1 Overview

From 1973 to 1979 the Laramie Energy Research Center (LERC) and its successor LETC operated a series of UCG field tests south of the town of Hanna, Wyoming.

The first UCG test of this generation, Hanna 1 failed at first, trying to use hydraulic fracturing to create sufficient permeability for a forward gasification. But through perseverance and successfully trying reverse combustion to link wells, the test became a success. They got UCG to work well and demonstrated the feasibility of extending it laterally out to gasify more coal. They operated effectively in main forward gasification mode for five and a half months. Given all the challenges involved in all the subsequent U.S. field tests, getting the first test of this generation to work well was an impressive accomplishment. Technical failure or a severe safety incident could have derailed the entire U.S. program. This success paved the way for the major U.S. program that followed.

The Hanna tests used conventional monitoring water wells and thermocouple wells to monitor the process. Assisted by the AEC/DOE's Sandia Laboratory, they also used various advanced geophysical techniques to monitor the process and try to track the combustion fronts and growth of the channels and cavities. These are discussed briefly in Section 7.15. Following the UCG operations, post-burn drill-backs were used to delineate and characterize the cavities.

Counting the various defined phases and sub-phases, there were at least nine identifiable tests that are summarized in Table 1. The detailed sequences of operations in most of the Hanna field tests were complicated and are not easily summarized. They involved various combinations of activities involving various combinations of wells to accomplish (or attempt to accomplish) several of the following: establish air flow between wells (without burning), hydraulic fracturing, pneumatic fracturing, forward burn (before a reverse burn link), reverse burns to link various wells, and forward burns using a variety of reverse-burn-linked wells for injection and production. There were successes and failures at making each of these happen as planned or hoped for. Most test histories ended up being very different than their test plans. This does not mean failure. It means they were progressing up the learning and experience curve. Each test had its own convoluted operating history and story. The Hanna I test is described in some detail because it is compelling as the first test, and because two different approaches were tried for the first time in this program. The many details of all the other tests are beyond the scope of this report, but may be found in the references listed below. Very brief overviews are given here, with emphasis on the conclusions and lessons learned.

#### **4.2.2 Recommended references**

Bartke and Gunn (1983) provide an accessible summary of all the Hanna tests. A series of reports provides much more detailed documentation (Bartke et al., 1985). Fischer et al. (1977) provides a contemporary description of Hanna II Phases 2 and 3. Cena and Thorsness (1981) provide concise descriptions of the operations, sketches, and consistently-calculated material and energy balances. Shafirovich et al. (2011) include an intermediate level of detail on the geology, operations, and results.

#### **4.2.3 Site description for Hanna and Rocky Mountain 1**

The Hanna and Rocky Mountain 1 field tests were conducted in the Hanna Basin, about 5 km south of the town of Hanna, Wyoming (Figure 2). The Bureau of Mines chose this site from a list they compiled of 10 potential field sites, based on a good set of criteria defined during their 1971 re-assessment of UCG. Criteria included: seam thickness ( $> 6$  m) for performance, depth ( $\sim 120$  m) to prevent communication of produced gases to the surface, minimize subsidence, and target uneconomical coal; isolation from shallower seams that could catch fire; current uses that were insensitive to environmental impacts; and operational convenience. Bartke et al. (1985), Oliver (1987 and 1988a) and Oliver et al., (1991) provide detailed site descriptions. Most of the following details are for the adjacent Rocky Mountain 1 site, but they are applicable to the Hanna tests.

The target Hanna 1 seam totals about 9 meters thick, including 7 to 7.5 meters of rich coal, including a small central parting and thin high-ash stringers, plus a thin lean zone near the top and a thicker lean zone near the bottom. The coal rank is high-volatile bituminous C with a zero free-swelling index and no agglomerating characteristics. Various coal analyses reported for the Hanna tests were similar to the analyses reported for RM1 (Oliver, 1987). At the RM1 location, the average as-received proximate analysis was 8.8% moisture, 27.3% ash, 32.0% volatile matter, and 31.9% fixed carbon, with a heating value of 20,000 kJ/kg and 0.7% sulfur. The elemental composition on a dry ash free basis was 73.4% C, 6.0% H, 1.8% N, 1.5% S and 17.3% O. Bartke and Gunn (1983) report an average as-received heating value of the coal for the Hanna tests of 20,000 kJ/kg. Cena and Thorsness (1985) use a density value of

1363 kg/m<sup>3</sup>. It is not clear if these averages represent the entire 9 meters of the seam or the richer 7 to 7.5-meter center of the seam.

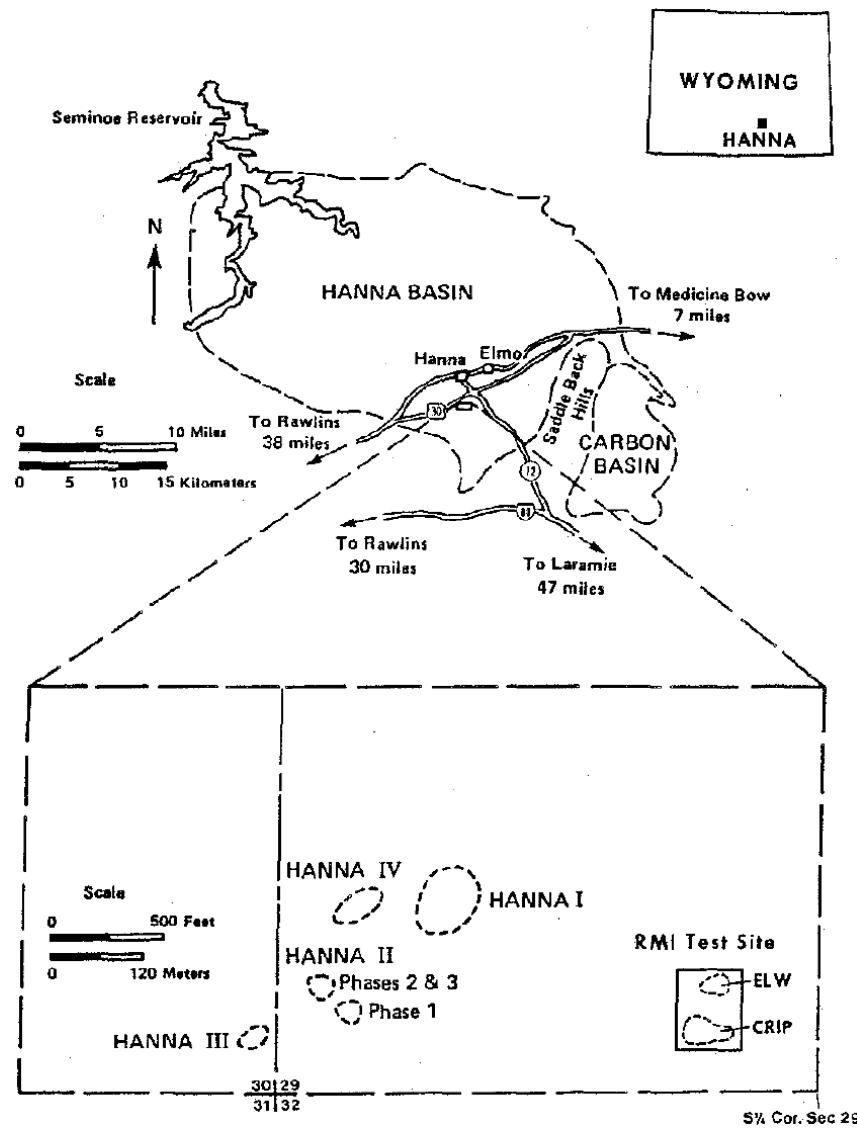


Figure 2. Location of the Hanna and Rocky Mountain 1 UCG field tests. (Oliver, et al., 1991)

Depths from the surface to the top of the seam near the center of the main cavity are listed in Table 1. The seam dips 7° to the northeast. Four identifiable units overlie the Hanna 1 seam. From seam to surface these are: a 15-30-meter lacustrine delta deposit characterized by fine-grained sandstone and siltstone, the strongest of the units; a 13-36-meter lower meandering river and floodplain deposit, characterized by mudstone and carbonaceous shale; a 0-65 meter braided stream deposit, characterized by fine to medium-grained sandstone with subordinate conglomerate (not present at the Hanna III site); and the youngest fluvial unit. Several coal seams are above the Hanna 1 seam but they are thin. A major northwest-southeast trending normal fault is located to the northeast of all the UCG field tests, providing isolation from far-field fire spreading. The natural groundwater flow is cross-dip to the northwest.

Of the many field test sites used in the U.S., this is one of the two best for performance, all aspects considered, with Rocky Hill the other. It would be too shallow to allow sufficient isolation for modern environmental sensitivities.

#### 4.2.4 Hanna I

Six vertical injection/production wells ended up being used in various phases. Their locations are shown in Figure 3. Initially the hope was to simply run a forward burn from one of the central wells and produce from multiple wells around it without creating any defined links. Air acceptance tests showed insufficient flow rate to do this, so hydraulic fracturing was tried as a method to create sufficient permeability in the seam. A period of forward burn was tried after hydraulic fracturing, but the injection rate was low even at high pressures. Hydraulic fracturing had not adequately prepared the seam for forward gasification. Reverse burns were performed successfully to link the wells. This allowed almost six months of good forward burn gasification to follow.

##### 4.2.4.1 *Unacceptable forward burn after hydraulic fracturing*

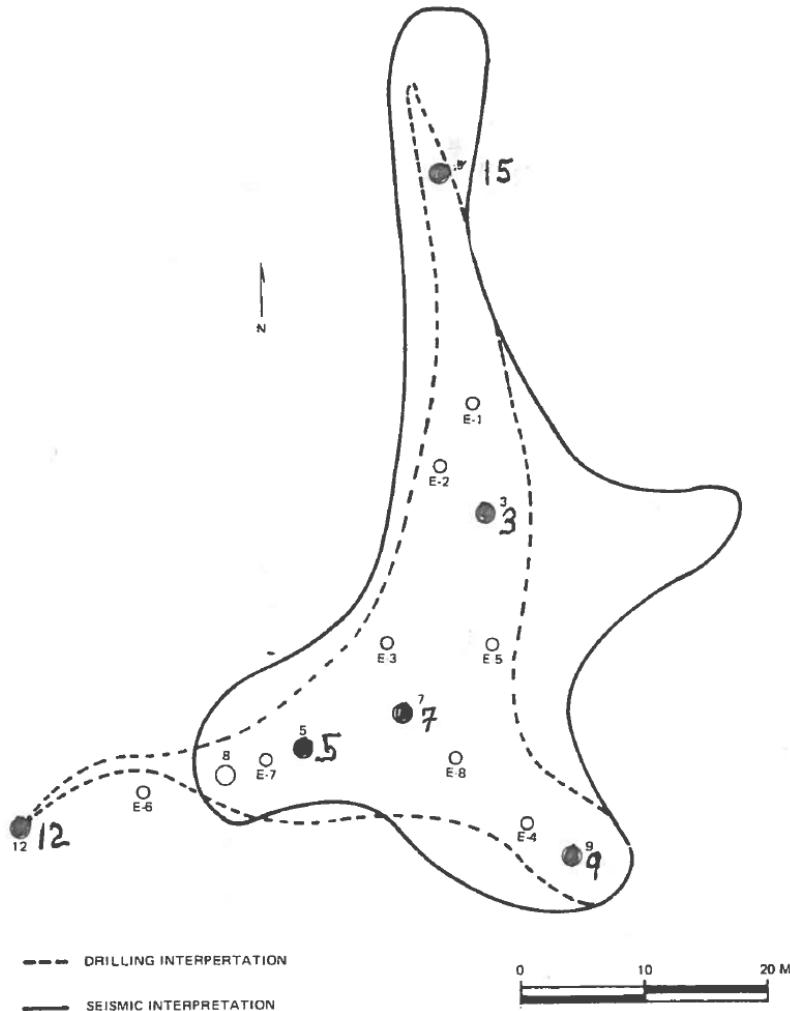
The central well 3, which had been cased to near the bottom of the seam, was used to hydraulically fracture the formation, using sand proppant and pressures of 37 bar. This is on the order of 10 bar over lithostatic pressure. Then, without any reverse-burn linking, the coal was ignited at well 3 using a downhole propane burner and a weak forward burn was operated by injecting air into well 3 and trying to produce out of multiple surrounding wells. Pressure drops were high, requiring up to 35 bar of injection pressure to get very low flow rates. This is on the order of 25 bar over hydrostatic pressure. Following more-severe plugging, this approach was abandoned after 60 days.

During this period, there were leaks in process well casings, there were uncased, uncemented boreholes in the area, and 90% of the produced gas escaped to the surface. Before the next phase, wells were recompleted and cemented. This decreased the product gas loss to about 45% for the subsequent reverse burn operations, and to immeasurably small for the main forward burn operations that followed.

##### 4.2.4.2 *Reverse burns between five wells to form a “Y” pattern of links*

Starting with the small burn and cavity near well 3, a series of reverse burns were used to create low-resistance channels within this already-fractured formation. They first created a reverse-burn link along the central 3-7-5 line, then drew links out from this central channel to two of the three perimeter wells, 9 and then 15. For these links, air was injected into both of the wells that they wanted to draw the link toward, and production was out of well 5 in the central line. The link completed first to well 9 and then to well 15. The recompleted wells reduced the gas loss to about 45% during this reverse-burn phase.

The successful linking of 5 wells into a short-armed “Y” pattern was a major accomplishment that allowed the next phase of forward burn operations be successful.



**Figure 3. Plan view of wells for the Hanna I test, showing outlines of the final estimated burned area. The affected coal was primarily in the top half of the seam. (Bartke and Gunn, 1983)**

#### 4.2.4.3 Six months of successful forward burns

From October 1973 to March 1974 a series of forward burn tests were conducted, using various injection and production wells, ultimately consuming about 3300 Mg of coal during this period. The best performance was during the first four of these months, with product gas heating values of 4.7 MJ/Nm<sup>3</sup>, gas production of 57,000 Nm<sup>3</sup>/day, and 20 Mg/day of coal gasified (75-80%) or pyrolyzed (leaving char) (20-25%). Gas loss was immeasurably small during this period.

During the middle of this period, a reverse-burn link was created from the main burn cavity out to well 12, extending one of the arms of the "Y" linkage patterns. This further established the utility of reverse-burn links to extend an on-going UCG operation out into new areas of coal. Estimates of the final cavity shape based on material balance, post-burn drilling, and a seismic survey are shown in Figure 3 above. The postburn coring showed that on average only the upper half of the coal seam had been consumed. This was attributed to linking between, and injecting/producing from wells that had not been cased to the bottom of the seam.

#### 4.2.4.4 Conclusions

The early Hanna 1 operations demonstrated that a forward burn will not work without a highly permeable pathway from the injection well and burn zone to a production well. Hydraulic fracturing with sand propping was not able to create a sufficient link.

Reverse-burns between wells proved able to create sufficiently permeable pathways for forward gasification. Process wells, instrumentation wells, and characterization boreholes must be completed and grouted well to avoid leaks. Links could be extended from well to well to create an initial network of linked process wells. Links could be made from peripheral wells to on-going burn cavities in forward-burn operation, providing a means of extending a UCG operation out to new areas of coal for longer project durations.

Forward burn operations readily tolerated many changes to the locations of injection and production wells, and were operated well for almost six months. Product gas quality declined with time as the test went on. By persevering and making use of reverse burn linking, the LERC team conducted successful, extendable UCG operation for over six months. This demonstrated UCG's technical feasibility, paving the way for a large, multi-site, multi-institution program that would last the next fifteen years.

#### 4.2.5 Overview of Hanna II, III, and IV

All the Hanna tests were remarkably similar to each other in their main aspects. They all used air injection. Oxygen-steam mixtures were never tried. All the Hanna tests used multiple vertical process wells that were linked by reverse burns. Reverse burns tried to link wells with various spacings, with and without preparation by pneumatic fracturing. The well patterns and intended link paths seemed to be the main design/preparation variable, and the choice and ordering of injection and production wells during the main forward gasification phases seemed to be the main operations variable. The general goal was to test well and link patterns for their scale-up potential; those that might allow high production rates, efficient sweep geometries, high resource utilization, and extension of the process to large and larger areas.

#### 4.2.6 Hanna II Phases 1A and 1B

They first tried to create a link between two wells by using forward combustion alone. This did not work. For Phase 1A they then created a reverse-burn link between two wells and then ran a forward burn for 38 days in a simple two-well configuration. The injection well for forward burn appears to be the up-dip well, with Figure 3 of Bartke and Gunn mislabeling the dip direction. Product gas quality declined over time, averaging 5.4 MJ/Nm<sup>3</sup>. Of the coal converted, 53% was gasified and 47% was pyrolyzed only. For Phase 1B they linked from the burn cavity to a third process well and ran a 38-day forward burn after that, injecting into the newly-linked well surrounded by new coal. This produced gas that varied between 7.1 and 4.8 MJ/Nm<sup>3</sup>, averaging 5.7 MJ/Nm<sup>3</sup>.

This seemed less ambitious than for Hanna 1. The main variable was injection rate. The following were conclusions. A forward burn will not proceed without a highly permeable link. Reverse-burn linking was simple and reliable. Reverse-burn linking used more air per linear meter when linking to a large burn cavity than when linking to a small ignited well. Forward burn is very robust to flow rate changes, and reaches a new steady state within two to four hours. Higher quality product gas resulted from low- to mid-seam links and earlier times when there is less roof involvement. Phase 1A was stopped and the injection point and burn location was moved to a new point in new and unburned coal, and re-started.

#### 4.2.7 Hanna II Phases 2 and 3

Two pairs of vertical process wells, 6 & 5 and 8 & 7 were completed to the bottom of the seam in an 18-meter square pattern, as shown in Figure 4. A reverse-burn link was created from well 7 (downdip) to well 8 (up-dip) using a down-hole electric heater for ignition of well 7. This did not go simply or reliably and involved a period of inadvertent forward burn and air pulsing to complete. This link would sit unused until Phase 3. For Phase 2 a second reverse-burn link was created between the other pair of wells, again going up-dip from well 5 to well 6. This also did not go simply or smoothly and took a month, and required injection pressures of 17 bar (about 10 bar over surrounding hydrostatic pressure). Indications were that the links were near the bottom of the seam as hoped for. Forward burn then operated between these wells for 26 days, injecting in well 6 and producing from well 5. By this time particulates had eroded the pipes, and after repairs, the produced gas temperatures reached 510°C, forcing shutdown after gasifying or pyrolyzing about 4100 Mg in forward mode.

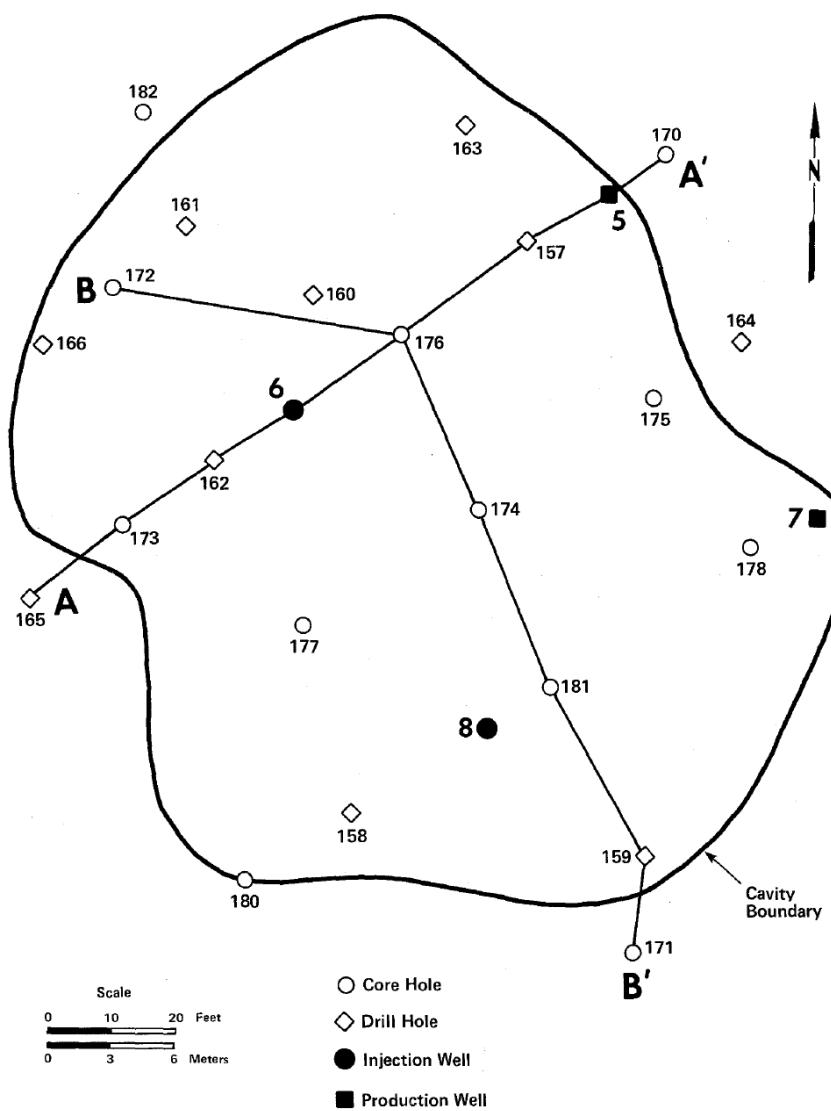


Figure 4. Plan view of process wells 5, 6, 7, and 8, and post-burn coring boreholes for Hanna II Phases 2 and 3. The outline shows the final estimated burned area for the combined two Phases. (Youngberg et al., 1983)

The plan for Phase 3 was to create an 18-meter wide reverse burn zone by injecting into both 7 and 8, intending to draw the burn from the full length of the Phase 2 burn. Only a narrow reverse-burn channel was created, from the large burn cavity to close to well 8. An attempt to do a “line drive” forward gasification from the 7-8 link to the Phase 2 cavity failed to even get started and this line drive was abandoned. Instead, forward gasification proceeded for 39 days with injection at well 8 and production at 7. An additional 4600 Mg of coal was converted during this Phase III. Product gas quality began high but declined during the month-long test, perhaps due to a combination of water influx and more roof involvement.

Figure 5 and Figure 6 show that the two forward burns connected and quite effectively gasified the volume between the four wells. They also show that the cavity extended upward far above the coal seam, and is full of rubble, including char and pyrometamorphic rock near the bottom that indicated temperatures exceeded 1200°C, and roof rubble above.

Conclusions from Phases 2 and 3 include the following. Reverse burns were achieved between wells with 18-meter spacing. Reverse burns do not always proceed easily. Reverse burns form narrow channels even when you are linking between broad injection lines and broad hot burn cavities. It is more common than not to suffer a decline in product quality with duration of a forward burn from a fixed injection point.

#### 4.2.8 Hanna III

The Hanna III field test was designed to assess the environmental consequences of UCG, as well as increase process technology development. Extensive pre-burn characterization of the groundwater and its hydrology were done, with water monitoring wells completed into the overlying aquifer and the coal seam. It is puzzling that the direction of water flow is shown to northwest or downdip, which is 120 degrees different than reported for the Rocky Mountain 1 location. It is also puzzling that no monitoring wells were completed into the coal seam in the up-dip direction where gas would be most likely to escape. The configuration was a simple two-well pattern with a reverse-burn link. Ignition and reverse-burn linking did not proceed easily but was finally accomplished. Forward burn was started, with the injection well and burn at the up-dip well. Production wellhead temperatures increase to 620°C after only 5 days. Water was added to the injection well and to a well near the production well. This allowed 38 days of forward gasification before the production wellhead again reached 620°C and the system was shut down. The 1983, six years after the test, the Hanna summary paper by Bartke and Gunn describe the large amount of environmentally-related data that were collected and were planned to be collected, but present no results. There is a hint in the report that gas moved out away from the active gasification zone. A challenge was that it took four years after the completion of the gasification for sufficient water to migrate back into the gasification zone to permit continuation of the groundwater monitoring program. Because coal has a high adsorption capacity for dissolved organic materials, it was hoped that the unaffected coal surrounding the gasified zone should retard the movement of dissolved organic materials.

Once again, linking was not straightforward, and high temperatures at the production well forced a shutdown. Clearly the program was still on the learning curve.

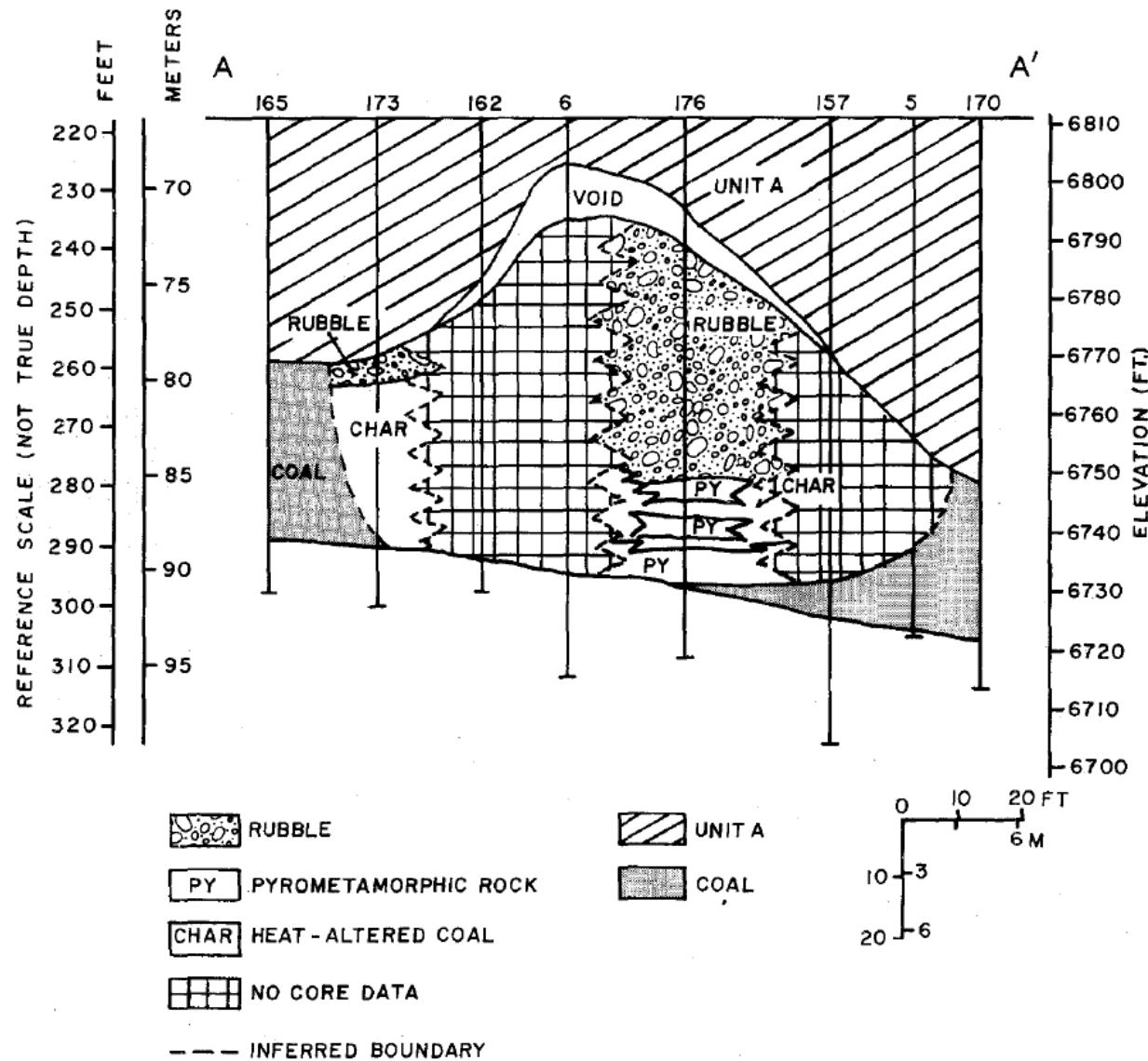


Figure 5. Cross-section along the axis of the Hanna II Phase 2 process wells based on post-burn coring boreholes following Phase 3. (Youngberg et al., 1983)

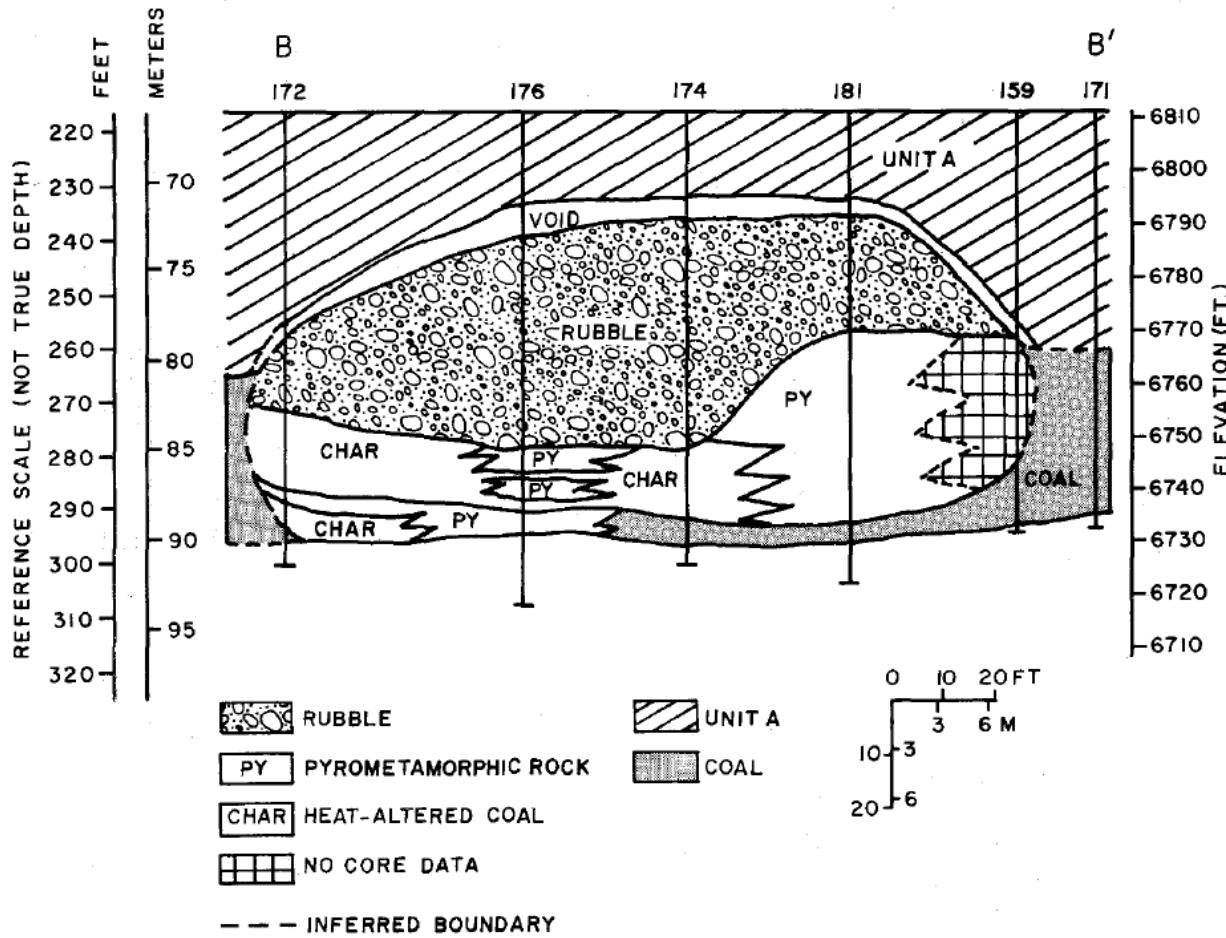


Figure 6. Cross-section cutting across the axes of the Hanna II Phase 2 and Phase 3 process well pairs, based on post-burn coring boreholes following Phase 3. (Youngberg et al., 1983)

#### 4.2.9 Hanna IV

Hanna IV was located close to Hanna I and slightly up-dip from it. Hanna IV's well layout, linking plan, forward burn plan, and actual linking and forward burn operations are too complex and full of problems for this scope. Repeated attempts to link across a 30-meter well spacing by reverse and forward burns at pressures up to 32 bar finally produced a marginal connection in a top over-ride location. Subsequent forward gasification periods were over-rides with high produced gas temperatures. Hydraulic fracturing was used. Reverse burn links were made up to separations of 23 meters. Most of the linking channels were at mid-seam or at the top of the seam, and in one case the major gas flow connection between two principal process wells was 25 meters above the coal seam, apparently because of poor well completions. Forward burn operations were short and gas product quality poor. They exhibited the previously seen trends of declining product gas quality with time, signs of over-ride of the burn to the top of the seam, and the problem of high product wellhead temperatures. Summary statistics are in Table 1.

Puzzlingly, Hanna IV seemed plagued with problems. The plan was not radically different than for all the previous tests – use reverse burns to link between various wells and do subsequent forward burns. After years of building experience and capabilities, Hanna IV had many operational and hardware problems,

including and especially in the linking phases and with well completions. The final operating history was very dissimilar to the plan.

Contributors to the problems may include one or more of the following. There were poor well completions. Previously undetected faults were found in the process area during post-burn evaluation of the site. It is possible that the hydraulic fracturing and high-pressure operations during the early phases of the nearby (within 50-100 meters) Hanna I test produced fractures and/or gas saturation in the Hanna IV area that affected things. It is possible that some of the experienced LETC principals had left for ARCO or World Energy.

In any case this demonstrated that while UCG's technical feasibility had now been demonstrated in the U.S., it was still very early in its technical development progression toward mature commercial operations. There was much that could go wrong and much more to learn.

#### **4.2.10 Environmental observations and conclusions**

The groundwater near the shallower Hanna III test was significantly depleted.

Despite high pressures used during the reverse burn operations, higher-than surroundings pressures used during some of the forward gasification periods, and calculated gas losses of 20% for the Hanna I, Hanna I-1A, and Hanna IV-A tests, groundwater quality investigations after the tests did not show high or wide-spread levels of contamination. Explanations for this surprising finding include the possibility that all the lost gas followed narrow channels that were missed by the groundwater sampling, the underground char, coal and carbonaceous shales may adsorb organics so strongly that they are not released into passing groundwater, or that the permeabilities of the surrounding coal and overburden are so low that no gas escaped into them.

Oliver (1988b,c) reported the following: "Since the [Hanna] UCG experiments were completed, dilute concentrations of pyrolysis products and leachates have been detected in groundwater monitoring wells in and near some of the six cavities. Three primary UCG indicator constituents have been measured at elevated concentrations: phenols, TDS, and sulfate. ... The indicated phenols contamination, however, was in groundwater sampled from a well which was previously used as a production well during the experiment." The Hanna I and Hanna III cavities were pumped and treated, with phenols not being detected in any of the pumped water. The depleted Hanna III groundwater was replaced with treated water from the Hanna I cavity. The Wyoming Department of Environmental Quality later released the site.

#### **4.2.11 Process and operations observations and conclusions**

Most importantly, Hanna I as well as the tests that followed, demonstrated in the beginning of this U.S. program that UCG was technically feasible. Later tests especially also demonstrated that it can be difficult, not go as planned, and is generally early on the development curve.

In general, the Hanna tests produced gas with a high heating value. This owes to the high heating value of the coal, thick seam, and modest amount of water influx and roof involvement (relative to the Hoe Creek tests).

The LETC team got a lot of experience with ignition and making reverse burn links. Sometimes this went easily and predictably and sometimes not. Failures led to changes in plans, using wells that would ignite or allow successful linking. These are discussed topically in Sections 7.1 and 7.3 later in this report.

Hanna I, and Hanna II Phases 2 and 3 demonstrated that reverse-burn links could be made from active or recently stopped burn cavities to new injection wells in unprocessed coal. This provides a valuable tool for expanding operations to larger scale.

It was important for both reverse burn linking and forward burn efficiency to have wells completed to the bottom of the seam.

Forward burns generally ran well and were robust, suffering gracefully through process upsets, large changes in injection conditions, and even temporary shutdowns.

Product gas heating values were usually very high at the beginning of forward gasification and declined more or less linearly with time, with the significant exception of Hanna II, Phase 2.

It is possible to switch around production and injection between multiple wells with considerable flexibility.

High temperatures at the production wellhead during forward burn operations were a recurring problem, several times requiring the operation to be shut down.

The Hanna I test was under-instrumented, making it difficult to follow the process underground. Later tests were instrumented much better with temperature wells and deployment of geophysical methods.

The average amount of overburden collapsing into the cavity for all six Hanna cavities was 9 meters, equal to the thickness of the coal seam. (Oliver, 1987).

Poorly completed and damaged wells caused problems. Erosion was one source of damage of production well piping.

### 4.3 Rocky Hill field test (ARCO)

ARCO's Rocky Hill field test is described here, a bit out of chronological order, because in many ways it was a continuation of the LETC/Hanna program. Although it was in a different basin at a deeper depth as Hanna, a very similar technical approach was used, as the leadership included some of the same people. As with all the Hanna tests, this consisted of multiple vertical wells, with linkages between them established by reverse burn, and a series of forward burns using injection from more than one of the vertical wells. Being a commercial test, there are few reports available; this summary is based entirely on Bell et al. (1983) and much information that would be of interest is not reported.

In addition to testing in the very thick Wyodak seam in the important Powder River basin, the goals included learning more about groundwater contamination, gas escape, and roof collapse and subsidence. Much collection activities and capabilities were put in place, quite a bit of data was collected, but little were reported. Much of this information must be inferred from a few things that are said, and much that was not said.

#### 4.3.1 Summary and site description

The Rocky Hill test was conducted about 60 km SSE of Gillette, Wyoming in the important Powder River Basin. This is perhaps 20 km SW of the Hoe Creek site and it targeted the thick seam for which the Hoe Creek site was originally chosen. The target seam was the 30-meter thick important Wyodak seam, whose top at this location is about 190 meters deep. It is a low-ash high moisture subbituminous type C coal and its as-received proximate analysis was 26.6% moisture, 5.4% ash, 31.8% volatile matter, and 36.2% fixed carbon with a heating value of 20,800 kJ/kg. It is overlain by semi-consolidated sandstone-claystone sequences including aquifer sand units.

Of the many field test sites used in the U.S., this is one of the two best for performance, all aspects considered, with Hanna-RM1 the other. Performance advantages are its very thick low-ash coal.

Performance disadvantages would be its wetness, high permeability in places and possibly weak wet overburden. It would probably be too shallow to allow sufficient isolation for modern environmental sensitivities, especially since consumption of the thick seam could lead to a tall zone of overburden collapse and fracturing if a large fraction of the resource was consumed, and the aquifers above it would be a concern.

#### **4.3.2 Wells, links, and summary of operations**

Three vertical process wells, P1, P2, and P3 were drilled and completed to the bottom of the seam in a straight-line pattern with 23-meter spacing. Six thermocouple wells and six HFEM wells were drilled under an agreement with DOE and LLNL.

Following the usual LETC-Hanna protocol of air acceptance testing, ignition, and air injection, reverse burn links were attempted. There was insufficient air flow to create a 46-meter link between P1 and P3. Igniting at P1, reverse-burn links were drawn to P2. More than one link occurred, and they were not straight, but they remained near the bottom of the seam and did not rise substantially. During forward combustion at P2, a reverse-burn link was drawn to P3 but never used later. The P1-P2 link took 10 days and the P2-P3 link took longer, consistent with Hanna experience of slower linking from a larger burn cavity.

Air-blown forward burn was established by injecting into P2.

#### **4.3.3 Performance data**

Forward gasification continued for 60 days at injection rates up to 80 mol/s, consuming 3270 Mg of coal. The gas quality was consistently high, generally above 7.8 MJ/Nm<sup>3</sup> and never dropping below 5.9 MJ/Nm<sup>3</sup>, and efficiency parameters were also high. This is consistent with the very thick seam delaying and minimizing thermal interactions with overburden material. Gas quality variations were associated with operating pressure (presumably via heat loss to vaporize water influx), flow rate, and coal collapse events.

#### **4.3.4 Operation observations**

Occasional operating problems were experienced, including surface piping plugging with tars and fines, and issues resulting from temperatures below -20°C. At no time did changes in subsurface activity create a situation where process operations had to be suspended. The injection well survived the 60 days but post-burn inspection showed its casing had separated as the result of overburden movement after the test had been terminated. Monitoring of the overlying sand aquifers did not indicate leaks during operation. The other process wells passed post-burn pressure testing and their cementing seemed intact.

#### **4.3.5 Cavity growth**

Post-burn coring was conducted to define the reactor geometry and both the vertical and horizontal extents of coal gasification were determined. No sketches were presented based on this or thermocouple or HFEM data. It was noted that “there was evidence that overburden material had collapsed above the coal seam.” A “collapsed zone above the coal” and “the collapsed region above the burn zone” were mentioned. Evidence suggests the cavity grew upward faster than outward. The amount of coal consumed is consistent with a cavity that is 13 meters in diameter and 26 meters tall. The height of overburden collapse above the coal seam was not reported.

### 4.3.6 Environmental observations

Considerable emphasis was placed on learning more about groundwater contamination, gas loss, and the impact of overburden subsidence on the overlying aquifers. 22 monitoring wells took pre-test background quality data and monthly samples after the 1978 test. In 1982 the report authors did not discuss the sampling results, other than to say “Generally, impact of the UCG test on water quality in the area has been less than that observed at the Hoe Creek UCG test site under similar circumstances.”, and [groundwater quality] has shown little effects from UCG; in general, water quality has returned to baseline ranges for most parameters.”

The product gas pressure at P1 was varied above and below hydrostatic and caused water influx and gas losses to change in the expected directions. They concluded that water influx could be adequately controlled with system backpressure without using dewatering wells for this small-scale test. The pressure at the injection well would have been higher than the pressure at the product well. The hydrostatic pressure of the surroundings at the top of the seam, where the cavity reached, would have been 3 bars lower than at the bottom of the seam. Estimates of gas loss were not published.

The vertical extent of cavity growth was sufficient to motivate the initiation of a subsidence monitoring program, including both down-hole and surface instruments. As of 1982, ARCO was still monitoring subsidence and reported that to date there had been no surface expression of subsidence.

Post-burn hydrology tests were conducted during 1981. Extensive multi-well interference drawdown and recovery pump tests were used to examine all three aquifers and to characterize the in-situ reactor region and the collapsed zone above the coal. This information is much-needed in the community but no results were presented.

### 4.3.7 Summary of observations and conclusions

UCG was conducted successful in a new coal seam in a new basin (for this team), and at a significantly greater depth than previous U.S. tests.

Technical operating results and observations were similar to the Hanna tests, despite the different setting. Reverse-burn linking was unsuccessful at a 46-meter spacing but successful at a 23-meter spacing. Reverse burn created multiple non-straight links. Forward burn progressed quite smoothly and was robust. The cavity apparently grew much faster upward than outward. There was gas loss and it increased when operating pressures were raised. Decreasing operating pressures increased water influx. The integrity of process wells, especially vertical injection wells, in the face of extreme thermal and mechanical stress is a critical issue that needs addressing to improve long-term UCG operational reliability.

“Ultimately, it is the site selected that has the greatest impact on the efficient and dependable operation of an underground reactor and on specific geotechnical phenomena such as well linking, overburden subsidence, process well completion and survivability, and groundwater interactions.”

## 4.4 The Hoe Creek Series of Field Tests (LLNL)

### 4.4.1 Overview

Lawrence Livermore Laboratory conducted three UCG field tests from 1976 to 1979 at the Hoe Creek Site in Wyoming. These tests were sponsored by the U.S. Department of Energy and its predecessors, with the Gas Research Institute cosponsoring the third of these tests. Consistent with LLL’s tradition, each test pioneered something new.

The Hoe Creek 1 test used explosive fracturing to create a packed bed of coal rubble and sufficient permeability to gasify much of the coal in between two vertical process wells.

The Hoe Creek 2 test retreated to the simple two-vertical-well, reverse-burn linked process, similar to LERC's previous Hanna II-1A and II-2 tests. However, Hoe Creek 2 included the first oxygen-steam injection for the first time in this era and made a medium-quality product gas. Hoe Creek 2 also added intensive instrumentation compared to previous tests.

The Hoe Creek 3 test pioneered three things. It demonstrated extended operation with oxygen-steam injection; it made use of the emerging technology of directional drilling to create a single link along the bottom of the seam with controlled location; and it pioneered and demonstrated the Extended Linked Well method (chosen for one of Rocky Mountain 1's modules eight years later), in which new UCG cavities could be ignited and burned at the bottom of different vertical injection wells that intersect a directionally drilled horizontal borehole link. These experiences were on the evolutionary path toward the invention of the CRIP process.

The second two Hoe Creek tests were intensively instrumented, much more so than the Hanna tests. This allowed the burn and cavity progressions to be followed remarkably closely, providing a good picture of how these complicated underground systems evolved. Although no one system of underground diagnostics can give all the information, a combination of several systems can be used to deduce a self-consistent description. The HFEM system and many thermocouple strings proved most effective. Given deserved criticism for choosing a shallow site, it should be noted that a deeper test would have made fielding so many downhole instruments too expensive and less would have been learned.

The process efficiency and gas quality of all the tests at the Hoe Creek site were relatively poor compared to most other sites. In addition to the over-ride problems that all sites wrestle with, the Hoe Creek coal seams that were gasified had a thick interburden layer and a weaker wetter overburden, as well as higher seam and overburden permeability for water influx, all leading to more heat loss per energy content of the consumed coal.

All the Hoe Creek tests, consistent with Hanna test observations, showed the benefits of having a low-seam injection placement and motivated efforts to find a more reliable way of accomplishing this.

Injection low in the seam delays the interaction of the developing burn cavity and the overburden for as long as possible. Heating and drying of inert wet overburden material reduces the amount of energy available for gasification and the result is a lowering of the quality of the produced gas. A bottom-seam injection also means that the injected reactants must permeate through a rubble of dried coal, char, and ash. This provides an efficient packed bed reactor situation, and helps direct gas flow out to the side walls and not up to the open void at the roof.

“Based on the experience of the Hoe Creek experiments two things were done. First, a new, more favorable site was sought [with low coal and overburden permeabilities] and a drier and more competent overburden. Secondly, a new method of performing the gasification process, the CRIP process, was conceived.” (Thorsness and Britten, 1989)

Hoe Creek has become infamous for its groundwater contamination and subsidence sinkhole. Its operation was not much different from other tests of that time. But the seams and overburden were more permeable and the overburden was much weaker. These factors may have led to more and contamination. It was also closer to the surface and overlain by an aquifer from which nearby wells were used for livestock watering and possibly human drinking, and it drains to downgradient wetlands. These factors generated a very intense post-UCG characterization activity and subsequent remediation project. The positive outlook on this is that it provided a small-scale alert warning to the community, a test-bed for

characterization and understanding, and played an influential role in motivating the development of improved practices for the future.

#### 4.4.2 Recommended references

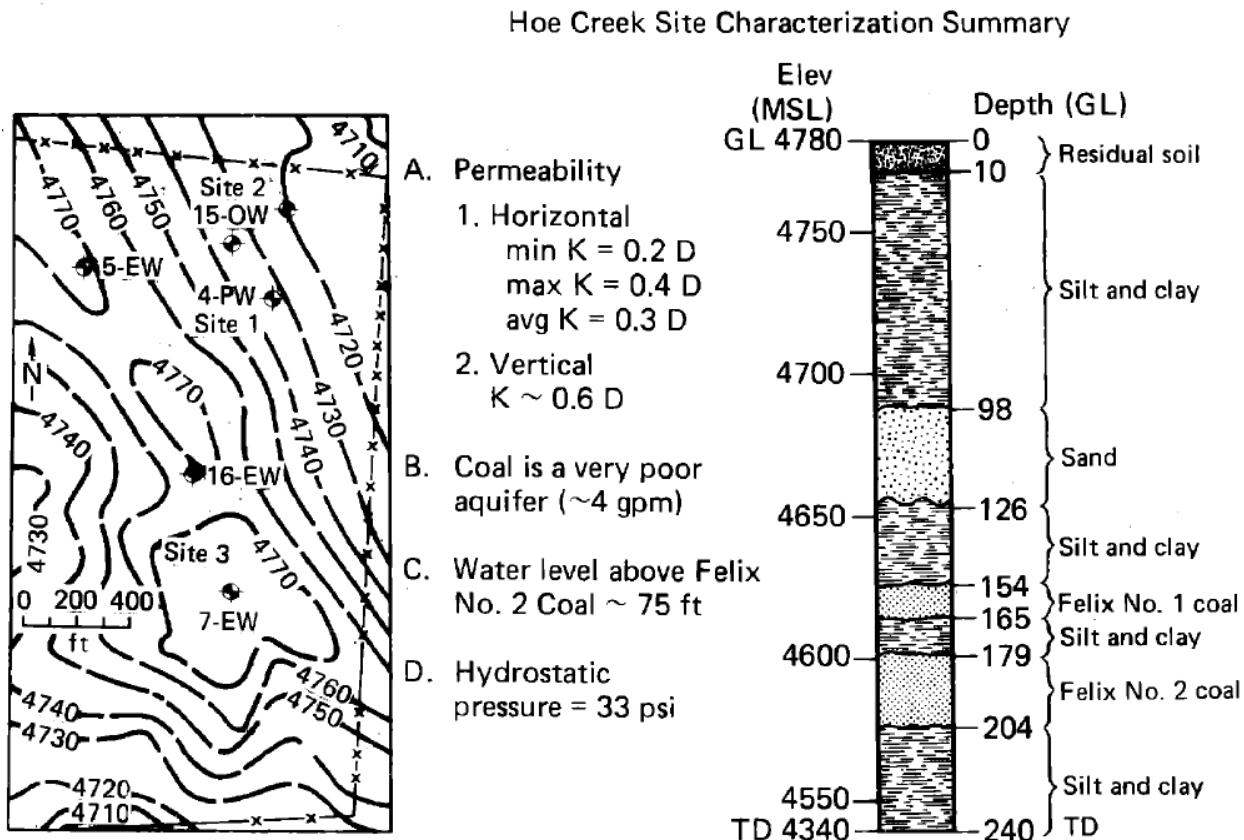
Stephens (1981) describes all the Hoe Creek tests and their results in detail. Thorsness and Creighton (1983) review the tests briefly and analyze them in the context of an energy balance. Cena and Thorsness (1981) contains very brief descriptions and extensive results on the energy and material flows over periods within each test. Thorsness and Britten (1989) provide a brief review, emphasizing accomplishments and conclusions drawn. Good topical reports on Hoe Creek 2 and Hoe Creek 3 also include, respectively, Thorsness et al. (1978), Aiman et al. (1980, and Hill (1981). Burton et al. (2008) summarizes the groundwater contamination issues well, and Shafirovich et al. (2011) is a convenient place to look for key information on the tests.

#### 4.4.3 Site description

The Hoe Creek site is in the Powder River Basin, in Campbell County Wyoming, about 40 km south of Gillette, on County Road 6041, 9 km west of Highway 59 on land controlled then by the U.S. Bureau of Land Management. This site had been selected after evaluating six – five on public land in the Powder River Basin of Wyoming and Montana, and one on Kemmerer Coal Company land in southwestern Wyoming. The evaluation criteria would still be considered excellent today. The Hoe Creek site was chosen intending to target a 30-meter seam that lay 300 meters deep at this site (probably the seam used in the Rocky Hill test). The much shallower and thinner Felix 1 and 2 seams were chosen for the first experiment to reduce its drilling costs, and as it turned out all three tests were done there.

These seams are subbituminous coals with low ash but high water. A typical as-received analysis for the Felix 2 coal is 29.2% moisture, 6.4% ash, 31.9% volatiles, and 32.5% fixed carbon, a heating value of 18,960 kJ/kg, and a density of 1350 kg/m<sup>3</sup>. The Felix 1 composition was similar.

Figure 7 shows the stratigraphy at the Hoe Creek site from the surface down through the 3.4-meter Felix 1 seam to the 7.6-meter Felix 2 seam below it. A different stratigraphic sketch notes the strata between and above the two coal seams as sand and sandstone, respectively. The intended target seam for these tests was the Felix 2 seam and process wells were always completed into it. But for at least HC2 and HC3, the burn broke through the 4.3-meter layer of weak rock between the seams and probably gasified almost as much Felix 1 coal as Felix 2 coal. From an energy point of view, it is perhaps better viewed as a single 15.3-meter seam, but with 33% ash instead and a correspondingly lower as-received heating value. The estimated depths to the top of the Felix 2 seam for each of the tests are shown in Table 1. The seams are horizontal; changes in seam depth primarily reflect changes in ground surface elevation.



**Figure 7. Left: Hoe Creek site test locations ("Site #") and surface topography; and right: stratigraphy near the HC3 field test. Units are feet. (Thorsness and Creighton, 1983)**

#### 4.4.4 Hoe Creek 1

LLL had earlier conceived of a large-scale UCG concept wherein explosives would be used to rubblize a 100+ meter square area of a thick deep coal seam and then gasify it from top to bottom as a fixed packed bed. Hoe Creek 1 was envisioned to be the first proof of principle that an explosively fractured coal seam could be gasified underground. In 1974 tests using 60 kg of explosives were done in an outcrop coal seam on Kemmerer company property in Kemmerer Wyoming. Coupled with this was geomechanical modeling of explosive underground fracturing, an area of Livermore expertise.

In November 1975, two 340-kg chemical explosive charges were set off simultaneously at the bottom of the Felix 2 seam, spaced about 7 meters apart. Cores examined after the blast showed moderate-to-heavy fracturing in the upper few feet of the coal bed, a lesser fractured zone in the middle, and a highly pulverized zone in the bottom 1.5-3 meters, in good agreement with model calculations. Extent of pulverization did not correlate well with permeability, which had been increased primarily at the top of the Felix 2 seam.

Process wells were drilled and completed to near the bottom of the seam at a 10-meter spacing, with much of the fractured zone between. In October 1976, it was ignited and gasified with air for 11 days. During this time, 112 Mg of coal was gasified out of the estimated 900 Mg of coal within the fractured region. The product gas heating value began at about 6 MJ/Nm<sup>3</sup>, declined to about 4.3 MJ/Nm<sup>3</sup> after 8 days, then fell to near zero over the next 3 days, averaging 4.0 MJ/Nm<sup>3</sup>.

The high permeability near the top of the seam resulted in active gasification and most of the flow to occur mainly at the top of the seam, diminishing the product quality. Based on the results of this test, explosive fracturing was abandoned as a linking/preparation step for UCG.

#### 4.4.5 Hoe Creek 2

##### 4.4.5.1 *Goals and instrumentation*

The basic UCG design and operation plan for HC2 was a simple 2-well reverse-burn linked process, but this had not been done in this geology. In addition to the usual testing of operating variables, an important test goal included a period of oxygen-steam injection to assess the feasibility of using UCG to make a medium-Btu gas that would be suitable for conversion to liquid transportation fuels.

Another test goal was to learn more details about the underground process, especially how the cavity grows and to assess various methods for monitoring the process.

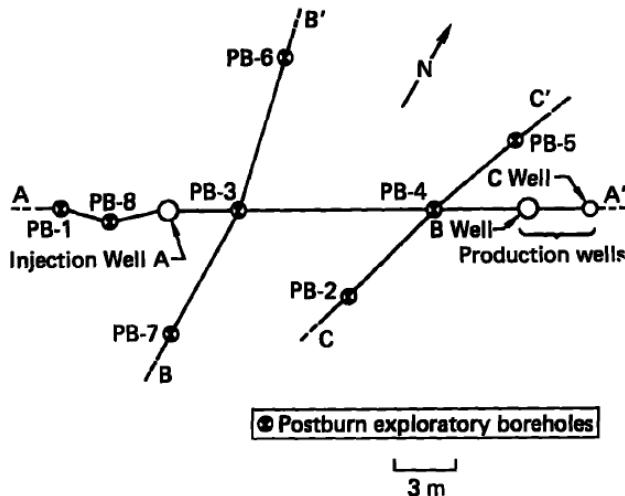
The process area was heavily instrumented. A total of 108 thermocouples in 15 wells were located in the expected cavity and surroundings. In addition, there were traveling thermocouples and gas sampling wells. Nine wells were used to create transmitting and receiving antennas for high-frequency electromagnetic-wave (HFEM) transmission measurements. A downhole inclinometer was designed and fielded to detect subsurface ground motion. To detect overburden subsidence, another set of wells contained extensometers, shear-strips to monitor for breakage, and piezometers. Nine water sampling wells were completed to monitor water quality. A helium-tracer injection and detection capability was deployed. (Fitting these tracer data during the summer of 1978 would be this author's first UCG job.) A total of 37 wells were drilled and instrumented

##### 4.4.5.2 *Wells, links, summary of operations, and performance data*

Two vertical process wells were drilled 18.3 meters apart and cased to within 0.3 meters of the bottom of the seam. The well plan is shown in Figure 8. Following air-flow testing and dewatering of the process wells, the coal was ignited at the bottom of the production well (B) in October 1977, using an electric ignitor in loose coal and wax-coated charcoal, with air injection into the injection well (A). The linkage proceeded smoothly, using an average of less than 5 bar gage injection pressure, at an average rate of 1.6 meters per day assuming straight line. In fact, thermocouples detected at least three reverse-burn channels, including two that extended  $\frac{3}{4}$  of the way to the injection well and one that extended the full way, which may have been the one located at the top of the Felix 2 seam. Gas loss during reverse combustion averaged 83%.

The forward burn phase began by gradually increasing the air injection rate to 20 mol/s over the first day, producing 5.6 MJ/Nm<sup>3</sup> gas but also large amounts of particulate dry coal and char. The many thermocouples and HFEM showed that initially the reverse-burn channels were carrying the flow, but they soon cooled off and all indications were that the by the second day the burn had over-ridden to a pathway (possibly the initial reverse-burn link) at the top of the seam. The gas heating value declined dramatically and the suspicion, later confirmed, was that the casing of the injection well had failed at the top of the seam and air was being injected at the top of the seam rather than the bottom as originally constructed. Injection was switched to a small 5-cm stainless steel pipe (intended for dewatering) within the injection well, thus delivering injection gas once again to the bottom of the seam. The gas quality recovery following this operation was dramatic, within an hour, demonstrating clearly the benefit of injecting at the bottom of the seam into coal (or coal/char rubble). This small tube limited the injection rate to 32 mol/s, but otherwise the test proceeded quite well. The gas

product heating value gradually declined as the burn cavity grew outward and very upward, and as was learned, more and more interburden (between the two seams) and overburden was dried, heated, and fell into the cavity, causing a significant heat loss. The average air-blown gas heating value was 4.1 MJ/Nm<sup>3</sup>.



**Figure 8. Hoe Creek 2 process well and postburn borehole (PB) plan. This also shows the cross-section lines used in Figure 9. (Stephens, 1981)**

After about two weeks of forward burn with air, a 2-day period of oxygen-steam injection was tested, converting 55 Mg of coal. With the casing gone, the injection point was again at the top of the seam. Nonetheless, the product gas heating value rose to 9.8 MJ/Nm<sup>3</sup>.

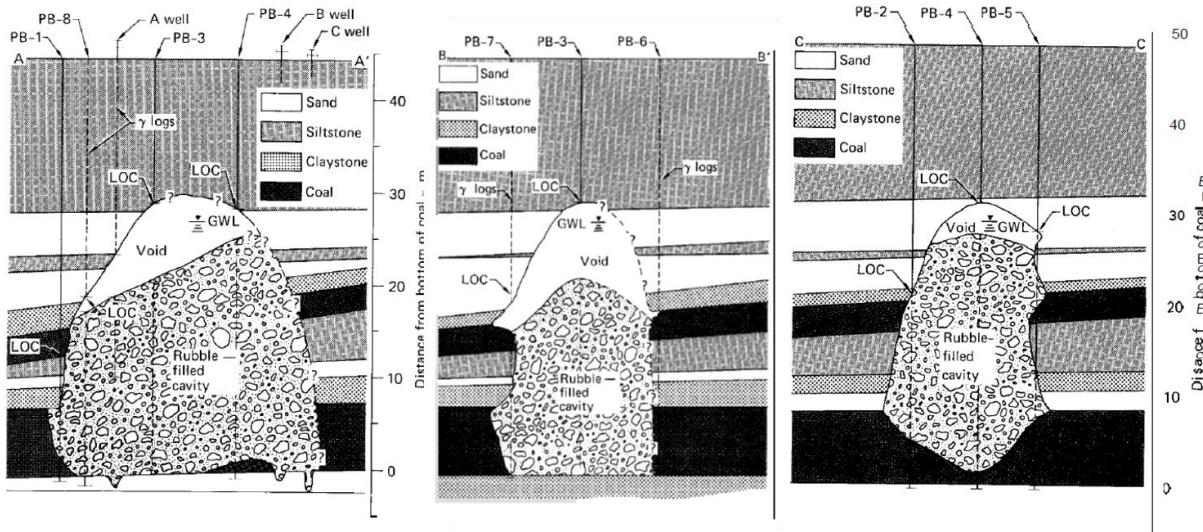
Air injection was returned to the small pipe that reached the bottom of the seam, returning the gas quality to 5 MJ/Nm<sup>3</sup>. This steadily declined over the remaining 43 days of gasification to 2.3 MJ/Nm<sup>3</sup>. The decline correlated with heat loss to the overburden material that had been exposed, dried, heated, and spalled into the cavity, extending 20 meters up above the seam. By this time a significant fraction of the coal was being burned so that it could dry and heat the rock above. The rock did not serve as an insulator because it kept spalling into the cavity, exposing fresh rock on the ceiling or wall surfaces (Camp et al., 1980, Krantz and Gunn, 1983c).

The total duration of air-blown forward gasification was 56 days, during which 2,470 Mg of coal was gasified or pyrolyzed.

Efforts throughout the test to reduce water influx by increasing cavity pressure were generally not very effective and cause gas losses that averaged 11% and 22% in the two main forward burn periods.

#### 4.4.5.3 Cavity growth

Figure 9 shows the final cavity boundary and contents based on thermocouple and HFEM data, material balance, and post-burn coring.



**Figure 9. Hoe Creek 2 postburn cross-sections (See Figure 8 for cross-section locations). Scale in meters. (Stephens, 1981)**

#### 4.4.5.4 Observations and conclusions

The first underground gasification of coal using oxygen-steam injection was done, at least for this generation. It worked well, more than doubling the product gas heating value, despite the unfortunate injection location at the top of the seam.

The comparison between two different injection points, one at the top and one at the bottom of the seam showed clearly the importance of injecting at the bottom. The lack of control over the location of the reverse burn link(s), with one likely at the top of the seam, was identified as a problem.

Engineering and construction of the process well completions, in this case the casing, is crucial. Failure of the injection casing at the top of the seam handicapped this test.

The cavity grows up faster than it grows sideways. It burned/eroded/spalled through the 4-5 meter interburden, consumed Felix 1 coal, and continued to spall its way up through the weak overburden. This thermal involvement of overburden rock and the water it contained is a significant energy sink, hurting process efficiency and gas quality.

There was an imperfect correlation between water influx and operating pressure, and high pressures cause high gas losses. Part of this was due to water entering the process by drying of coal (if its daily drying rate is different than its daily gasification rate), interburden and overburden, and permeation. Decreasing pressure allows more water to permeate in, but increasing pressure causes gas loss at the higher elevations, while not being completely effective at stopping inward permeation at lower elevations. A better site would have lower permeability.

#### 4.4.6 Hoe Creek 3

Experience at both Hanna and Hoe Creek II had shown that the paths of reverse burn links could not be controlled, they were often multiple, and often included a link along the top of the seam. In addition, Hanna IV had recently experienced a great deal of difficulties trying to accomplish longer reverse-burn links. Directional drilling technology was improving and Livermore decided to use it to control the placement of a long link near the bottom of the Felix 2 seam for the Hoe Creek 3 test. Injection and

production wells would be vertical wells intersecting the horizontal link. Air would be used to get the burn going and stabilized and then oxygen-steam would be used for the remainder.

The test was intensively instrumented with thermocouples, HFEM, in-situ geomechanical instruments, water sampling wells covering both seams and overburden, and tracer injection and detection.

#### **4.4.6.1 *Wells, links, and summary of operations and performance***

Figure 10 shows the main process wells. DD1 was a 7.6-cm directionally drilled borehole to be used as the link. It ended up being about 2 meters above the bottom of the Felix 2 seam. The production well for the entire test was B. Well A and P1, 30.5 and 41 meters from B were the main and back-up injection wells. Wells P1 and P3 were for pumping water out of DD1. Wells B and P3 intersected DD1 when drilled. Wells A and P1 were connected to DD1 using a water jet drill. Well C, 30 meters downstream from B was intended as an additional production well to expand the scale of the test, but the water jet was not able to connect it to DD1.

It appears that the process wells were cased to down to their intersection with DD1, about 5.6 meters below the top of the Felix 2 seam. Based on the injection well failures at the top of the seam at Hoe Creek 2 and some of the Hanna difficulties, they were specially designed to withstand both mechanical and thermal insults, with high-temperature external grouting, an external casing, water cooling injection between that and a second casing liner, and a 3-inch pipe “lance” inside of that for oxygen injection, with air and steam injection to be in the annulus between the oxygen pipe and the larger liner. Despite this effort, new and old failure mechanisms would cause problems described below. The provision for an alternate injection well was wise.

The flow resistance of the 7.6-cm borehole link was reduced using a quick, oxygen-enriched reverse burn along it that stayed with the link. The coal consumption and flow resistance were consistent with expansion of the link to an equivalent 15-cm diameter. (A reverse burn will not propagate upstream in a borehole without oxygen enrichment.) To start this, well B was ignited at the bottom by lowering an electric ignitor and covering it with crushed coal.

Forward burn with air was started in well A and the flow rate ramped up to get the cavity and burn started. The cavity expanded up as fast or faster than out and the burn zone reached the roof of Felix 2 and heated/spalled some distance into it within only 4 days. The increasing heat loss to heating and drying of overburden material caused a change in gas composition and a decline in product quality. A total of 7 days of air forward burn consumed 240 Mg of coal (equivalent to a 7-meter diameter sphere). The product gas heating averaged 4.5 MJ/Nm<sup>3</sup>. This and the composition matched closely the first ten days of Hoe Creek 2.

During preparations to switch to oxygen-steam injection, it was discovered that the oxygen pipe “lance” in well A had plugged. It had extended 30 cm below the larger liner and the hypothesis, supported years later in the Centralia experiments and excavations, was that molten slag had plugged it.

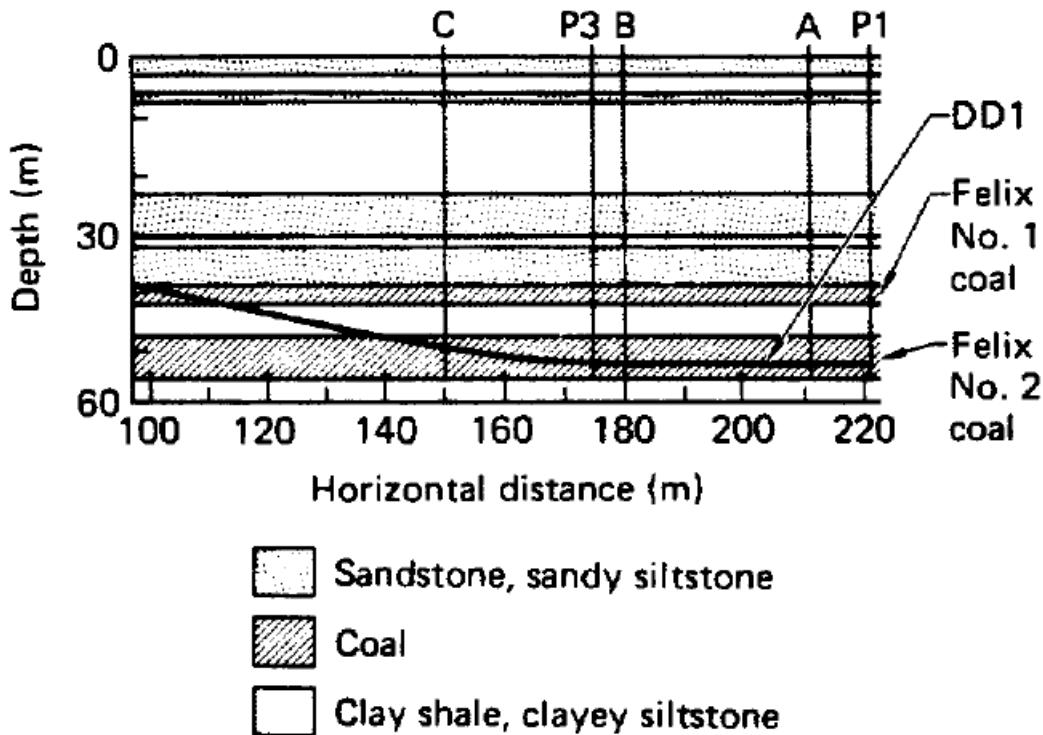


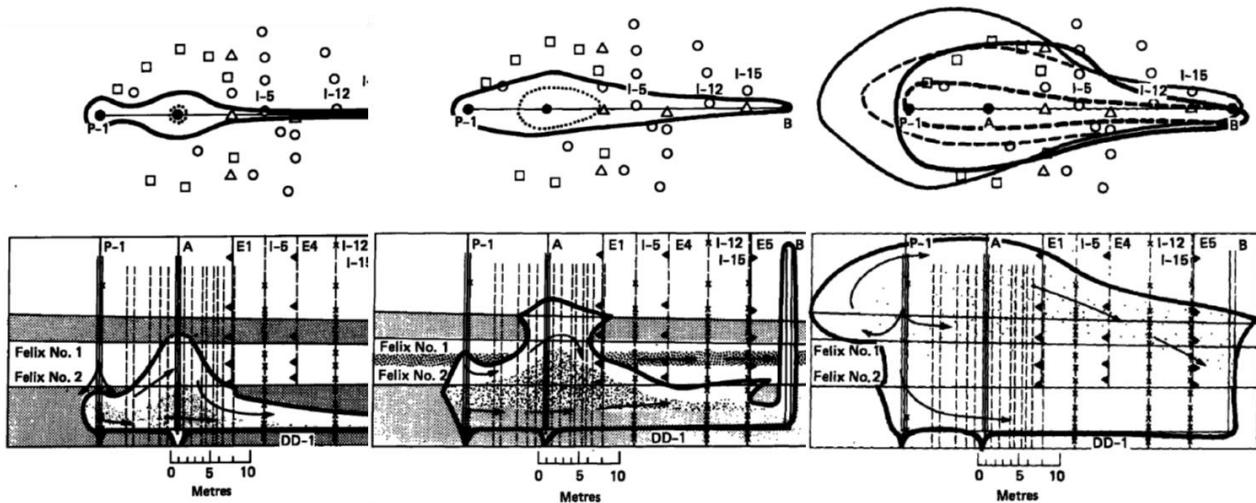
Figure 10. Cross-section of Hoe Creek 3 showing main process wells, B (production), A and P1 (injection), P1 and P3 (dewatering), and C (intended production, not used). (Thorsness and Creighton, 1983)

The injection point was switched to the backup injection well, P1, along the directionally drilled link, oxygen-steam was injected, and within 2 days the burn near well A had moved back to P1 and was expanding a cavity there. This was the first demonstration of the Extended Linked Well process, in which new UCG cavities could be started and expanded at the bottom of a series of vertical injection wells intersecting a directionally drilled horizontal borehole link.

Injection was switched between wells several times for different reasons. The injectants and injection points were:

- 7 days of air into A at the DD1 elevation
- 7 days of oxygen-steam into P1 at the DD1 elevation
- 7 days of oxygen-steam into A between the Felix 1 and 2 seams
- 33 days of oxygen-steam into P1, probably at the Felix 1 elevation

The intensive monitoring instrumentation, mainly HFEM and thermocouples, allowed the burn zones, cavity growth and gas flow to be followed in considerable detail. It was very complicated and involved coal burning and spalling near both wells, faster upward growth in coal than outward growth, expansion through the interburden and then the Felix 1 overburden by a combination of small-scale spalling and detectable collapse events, and gas flow through both cavity rubble and even lateral flow through a sand zone within the interburden. Figure 11 shows the cavity boundaries after 9, 13, and 54 total days of gasification.



**Figure 11. Hoe Creek 3 cavity boundaries following: a) 7 days of air injection into A plus 2 days of oxygen-steam injection into P1; b) 7 days air into A and 6 days o-s into P1; and c) 7 days air into A, 7 days o-s into P1, 7 days o-s into A, and 33 days o-s into P1. In the plan views of a) and b), the solid line is Felix 2 and the dotted line is Felix 1. In the plan view of b), the thick dashed and solid lines are the DD1-level and top of Felix 2 and the thin dashed and solid lines are the bottom and top of Felix 2. (Stephens, 1981)**

The initial borehole link quickly evolved into a vertical slot, then a tall “V” shape, presumably filled with dried coal and char rubble. It presumably evolves by hot gas flow drying and then pyrolyzing the coal, with small-scale spalling of coal and char creating the rubble. The slot quickly reached the top of the Felix 2 seam but only eroded the interburden above it slowly, never breaking through to the Felix 1 seam. The slower progression up into the overburden rock was probably due to lower gas temperatures there than in the main burn cavity.

The 47 days of oxygen-steam injection gasified 3550 Mg of coal, but the product gas heating value averaged only 8.4 MJ/Nm<sup>3</sup>. By the time oxygen-steam injection started, the cavity and burn had already reached the interburden near well A and would quickly reach it near P1. For most of this period, most of the gasification was of the 3-meter Felix 1 and the top of Felix 2, with heat losses to the 5-meter interburden and the overburden. There was a small decline through this period, mainly reflecting an increase in the ratio of rock to coal involvement.

#### 4.4.6.2 Process observations and conclusions

HC3 demonstrated yet again that it is very difficult for a vertical injection well to survive in the harsh UCG environment surrounding it. Despite considerable efforts to assure the durability of the injection wells, multiple failures and upward erosion of liners occurred, including plugging with slag, thermal melting/attack, and mechanical insult from collapse events. Holding an injection point at the bottom of the seam as desired is difficult with a vertical well because it is at the center of oxidant injection (more of a problem with the hotter oxygen-steam burns than air), and it is at the center of the cavity and subject to more collapse events if they occur.

UCG cavity growth, both in coal and in overburden tends to grow up easier than out, and holding the injection point low is difficult.

Gasification of the lower Felix 2 seam was probably limited by the tendency of the burn to move up and over-ride, and because the interburden fell and covered it with rock rubble and slag.

There were distinct observable collapse events of the interburden, with its erosion likely due to a combination of these and small-scale spalling/fracture/rubblizing events.

It was possible to switch injection wells and points,

The forward burn process was robust to sudden changes in the injection point and in switching back and forth between oxygen-steam and air (There were also several short periods of air injection during the main period of oxygen-steam injection, mainly due to equipment problems.

The experiences of Hoe Creek 3, adding to those of all the other field tests to date, were on the path towards the development of CRIP. The need to keep the injection point low had repeatedly been learned. The decline of performance after the cavity reached the roof and experienced those heat losses had been seen repeatedly. The benefit of switching injection points from an old big cavity into new coal had been seen. The use of directional drilling to create an in-seam borehole had gone well. And at HC3, a new injection point along a horizontal production borehole was used to start a new burn location in new coal. The seeds of CRIP had been sown.

Despite a defined initial borehole link, the actual link channel evolved rapidly into a tall steep-sided “V” of dried char and coal rubble growing rapidly to the top of the seam. For most of its length it appears that most of the flow is near the top of this. The importance of creating the link at the bottom of the seam became less certain after this experiment. It probably helps in the beginning and might help in certain other designs, such as CRIP, that can keep the injection point low.

High particulate loadings and associated erosion of piping were observed, as they had in some of the Hanna tests.

“The Hoe Creek site [at least its Felix seams] was not an easy place to perform a high-efficiency UCG process. The coal seam was too permeable, allowing both excessive gas losses and detrimental water permeation influx. The overburden was relatively incompetent, allowing a great deal of wet inert material to enter the process to the detriment of the gas quality and energy efficiency.”  
(Thorsness and Britten, 1989)

#### **4.4.6.3 *Groundwater contamination and environmental aspects***

Three weeks after the end of gasification, surface subsidence began, creating a steep-sided crater in between wells A and B about 3 meters deep and 9-18 meters across. Communication with the cavity was evidenced by some steam escape from the crater.

The extension of collapse up to the surface is more evidence of the overburden weakness at this site. It probably happened at HC3 and not the shallower HC2 because of the greater lateral extent of the cavity at the Felix 1 level, and the taller and especially longer and wider vertical extent of the cavity up into the overburden. The delay of the collapse may be related to re-infiltration of groundwater into the area making the overburden heavier (White, 2012)

The upward growth of the cavity and later sink-hole, and the dual mechanism of thermal/drying spalling and mechanical collapse events suggests that a better understanding of these phenomena is needed, and that overburden rock structural strength and resistance erosion by heat-induced spalling is an important factor in site selection.

Gas losses were estimated at 20%. The system pressure was about 2.5 bar gage and was decreased slowly through the experiment. This may have been about equal to the fluid pressure in the surroundings in the lower part of the lower seam, but was probably higher than the surroundings at the top of the cavity. The tall vertical growth of open/rubble cavity and possibly even taller fractures into the overburden probably made the process gas pressure at these upper elevations greater than the water pressure in the surroundings, causing gas to escape at rates and pathways governed by the permeability field.

Water monitoring samples showed elevated concentrations of phenols, organics, and inorganic species. This led to an extremely intensive, long, and extensive characterization investigation and remediation. The details are beyond the scope of this report. They are reviewed and summarized by Burton et al. (2008) and reported on exhaustively in technical and regulatory papers and reports. A general note is that low vapor pressure components tended to condense out near the cavity and gases were carried further. Even volatile organics tended to stay near the cavity by mechanisms that included being dissolved into immobile tars that reside in coal cleats.

Had the exact same test been done in the exact same geologic materials using the same pressures relative to surroundings, it is likely that the same vertical cavity growth would have occurred, the same connectivity with higher-permeability overlying aquifers, the same 20% gas loss, and the same production and transport of contaminants into the surroundings. It is possible that the sensitivity to these changes would be less if it were further from the surface and not in aquifers that were used for livestock and possible human consumption.

The several Hanna operations were of similar scale as Hoe Creek 3 and 2, over-pressured similarly if not more in attempting to keep water permeation out, and some had similar amounts of gas escape. Yet groundwater sampling at Hanna found much less contamination. Lower permeability of coal and overburden and stronger overburden at Hanna may be reasons. Less intensive investigation may be another, as that site was deeper and under a less sensitive area.

The contamination problems at Hoe Creek led to greater attention to this problem, including careful permitting, planning, and operational improvements at Rocky Mountain 1, including the development of the Clean Cavern Concept there.

## 4.5 The Rawlins Steeply Dipping Field Tests (Gulf)

### 4.5.1 Overview

Gulf Research and Development Company operated the two Rawlins tests under shared funding with the Department of Energy. A good summary report that covers both of Gulf's Rawlins tests is Bartke (1985), which also includes a comprehensive bibliography of Rawlins and steeply-dipping bed work. Gulf's Rawlins 1 test is described in detail by the combination of Gulf (1981) and Davis et al. (1981). Additional details will be found in the UCG Symposia of those years.

These were done in the steeply-dipping (63° down to the SW) "G Seam" of subbituminous coal about 70 km west of Hanna in the Fort Union formation at the North Knobs site on the west flank of the Rawlins Uplift. The true seam thickness is about 7 meters, +/- 2 meters. As-received proximate analysis was 14.6% water, 5.0% ash, and 35.4% volatile matter, with a heating value of 23,550 kJ/kg.

During one of the tests, process gas found its way up the seam and into an operations trailer sitting above the seam. Process gas also leaked up along a well between the grout and the formation.

#### 4.5.2 Rawlins I

Rawlins I was mainly a fairly small air-blown test with a smaller oxygen-steam phase at the end, conducted in October to December of 1979. Figure 12 shows a cross-section. The injection well, AIW, was directionally drilled below the seam, entered the seam from below, and was cased near the bottom of the seam at a vertical depth of 122 meters below the surface. The production borehole and link, PGW, was directionally drilled along the bottom of the seam to below the injection well, and completed and cased to a point about 15 meters up-dip from the injection point. The injection point at the end of the AIW casing was ignited using triethyl borane (TEB) added onto a gasoline-diesel mixture. Air acceptance testing at 25 bar created enough fracture permeability to allow the 1.5-3.0-meter reverse-burn connection (between the imperfectly drilled wells) to be made by injecting at 15 bar. These procedures went quite smoothly, with the most difficult part getting sufficient air flow for the short reverse burn connection.

Forward burn was started by air injection into AIW with production up PGW. Figure 12 above shows the coal cavity growth. The reactor apparently grows via periodic dropping of large chunks of coal and roof rock into the base of the reactor. A rubble bed was established over the base of the AIW-1 and served as a fire-pit. In the early stages of the process, the oxidation and reduction zones were confined in the rubble bed.

Geophones, thermocouple wells, and post-burn boreholes indicated the cavity expanded significantly up into the roof rock that was vertically above the gasified coal cavity. The coal cavity was approximately 17 meters long, 11 meters wide, and 6 meters high. The overburden cavity volume was free of rubble, water filled, and had a volume of about 210 m<sup>3</sup>.

In total, 1513 Mg of coal were consumed over 30 days of forward burn with air injection and 5 days at the end of oxygen-steam injection. The air phase produced gas of high quality. (6.0 MJ/Nm<sup>3</sup>). The high quality was consistent with the high heating value of the coal and the relatively small ratio of roof rock involvement to coal consumption. The seam is 15 meters thick vertically in this small test.). Cena and Thorsness (1981) estimated negligible gas loss.

Some product gas leaked up the coal seam to a surface outcrop, and up the outside of the production well, but not enough to significantly affect recovery. There were small groundwater excursions in total organic carbon and ionic salts.

Test conclusions included: the feasibility of gasifying a steeply-dipping seam using a directionally borehole link and process wells was demonstrated and worked well; TEB-diesel worked well as an ignition method; the process works conceptually by coal falling from the upper face and walls of the burn cavity into a “fire pit” near the injection point, making continued falling necessary for efficient operation without bypass; product gas could be cooled well by using an air-insulated dip-water-delivery-tube extending into the production well; particulates in the product gas could be reduced by raising the reactor pressure which decreases gas velocity (but no mention was made of the disadvantage of gas loss, perhaps because the permeabilities were so low); gas loss up the coal seam or a permeable stratum may be a pathway for health and safety (CO or combustion) or environmental risks; wells, especially the thermally-stressed production well, must be cemented well to the formation to eliminate this gas pathway to the surface, and casing collar joints need to be tightened well during completions.

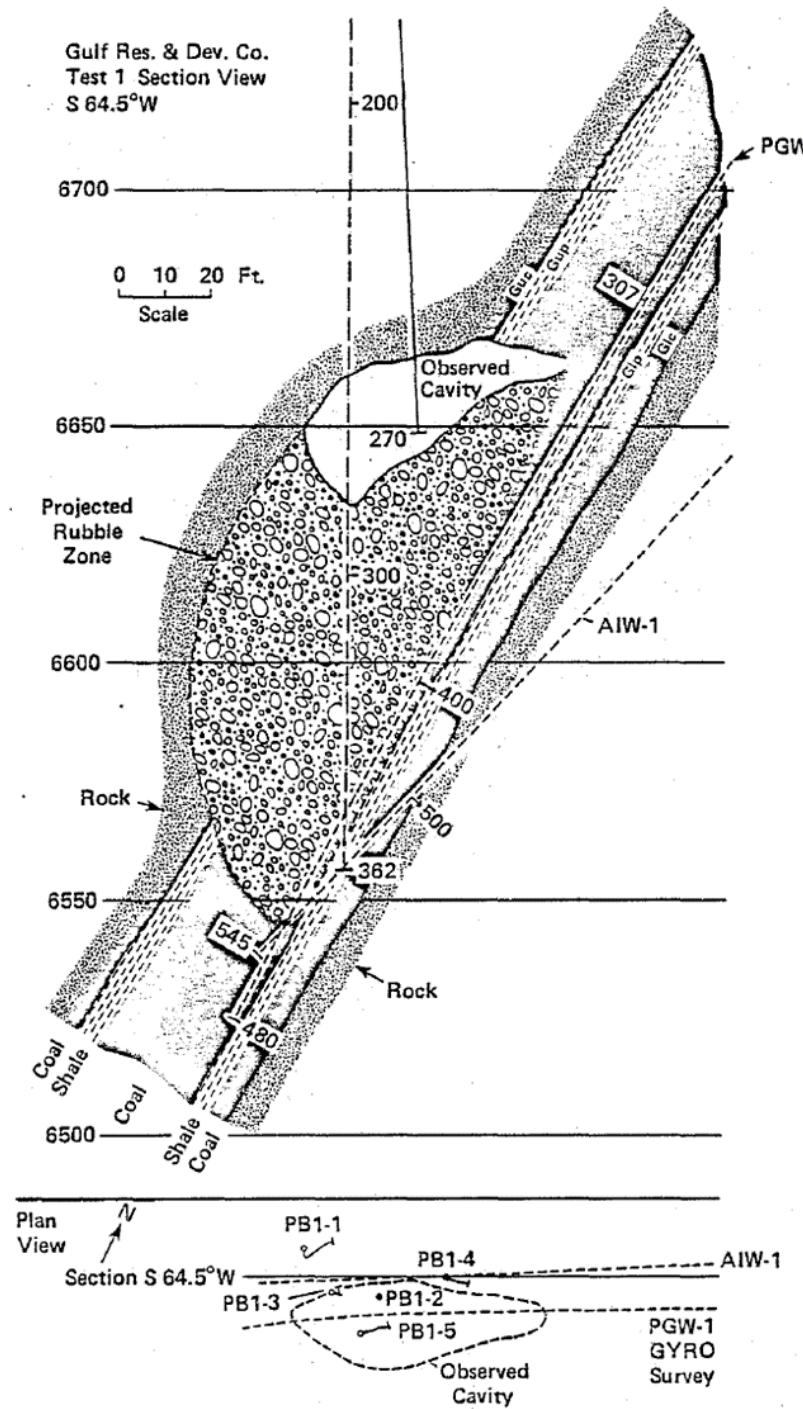


Figure 12. Cross-section of Rawlins I test after gasification. The injection well, AIW-1 was cased to about the 6550' elevation. The production well, PGW-1, was cased to about the 6600' elevation and continued down as a borehole in the seam past the injection point. (Bartke, 1985)

#### 4.5.3 Rawlins II

Figure 13 shows the four main process wells of Rawlins II. Rawlins II had a more complicated well pattern and plans, but ended up being two side-by-side modules, with Module 2 (VIW to SPW) being similar to Rawlins 1 and Module 1 (SIW to SPW) being essentially a large-scale version of Rawlins I. The slant production well and borehole, SPW, form the centerline. This is cased in the coal to a true depth of 122 meters and continued down in the seam as an open borehole to below the injection well points. The slant injection well, SIW, was completed to a true depth of 187.5 m, probably less than 10 meters across dip from SPW. The vertical injection well, VIW, was completed to a true depth of 170.1 m and drilled open another 12 m below that, about 6 meters across dip from SPW in the other direction. VLW was drilled but fell victim to ignition and linking challenges and was not part of the final configuration.

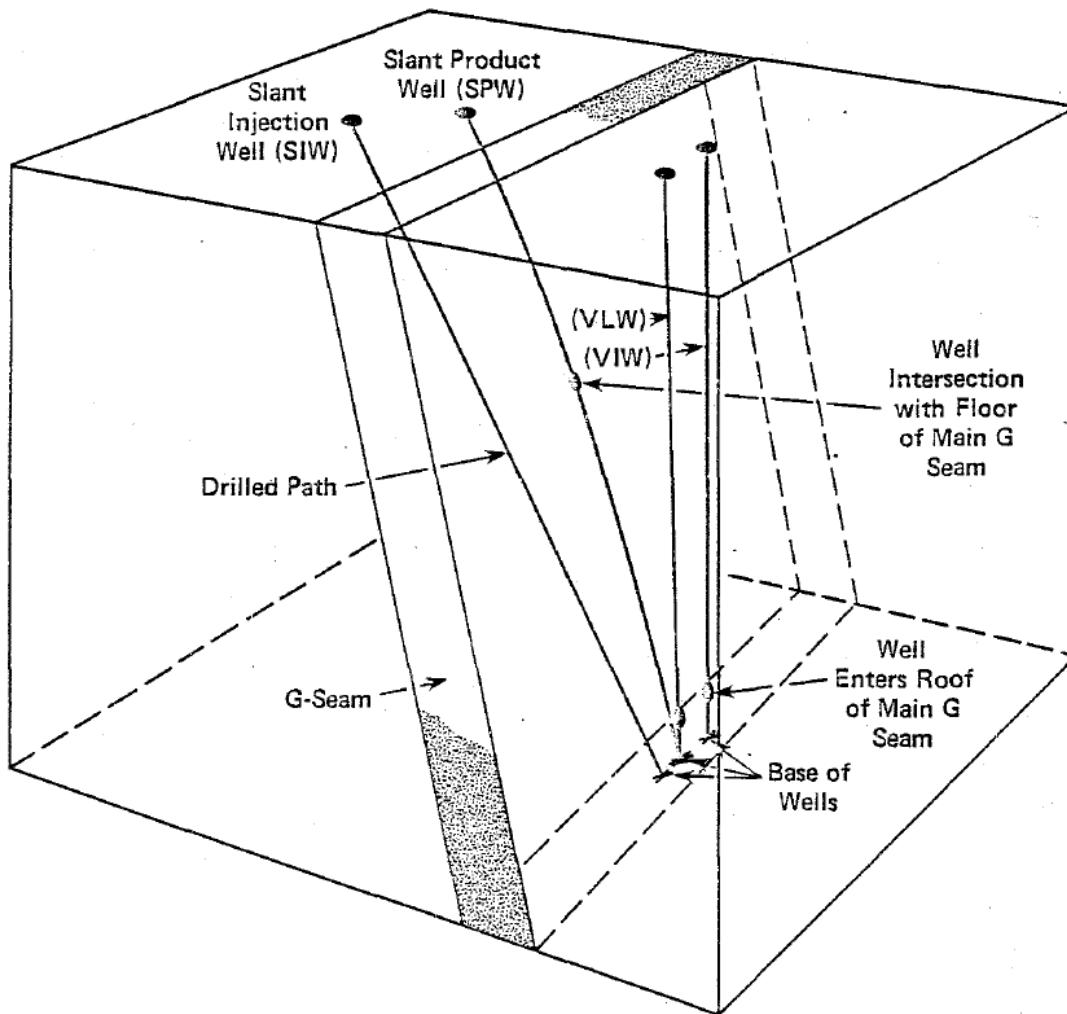


Figure 13. 3-D view of Rawlins II process well configuration. SPW was cased to 122 m of true depth and open borehole down below the injection well casings. SIW was completed to 187.5 meters of true depth. VIW and VLW were completed to 170.1 meters of true depth (different than pictured). Lateral spacing from the injection points to the SPW borehole were supposed to be 6 m. (Bartke, 1985)

In addition to many HFEM wells, four hydrological monitoring wells and 120 shallow gas sampling wells were drilled.

The full ignition and linking story for Rawlins II would fill a Russian novel and will not be recounted here. The TEB-diesel ignition technique did not go well. Reverse burn links were difficult and did not go where planned. VLW was destroyed. In the end, a reverse-burn link was made between SIW and the SPW borehole; it was thought to angle up steeply from SIW to intersect SPW. After forward gasification of Module 1 (SIW to SPW) for two weeks, a reverse burn link was drawn from somewhere in this cavity over to VIW.

Module 1 (SIW to SPW) ran for 10 days over two weeks, having to be shut down because of a combination of engineering (steam boiler, etc.) problems and cavity growth problems. Module 1 included only 3 days of main oxygen-steam operation that followed their experimental plan. The burn and cavity growth went up-dip instead of the intended cross-dip. Several HFEM wells were destroyed by the wayward cavity, launching water and hardware skyward at the surface (a fail-closed valve at the surface minimized gas escape).

Module 2 (VIW to SPW) ran for 13 days of forward burn after its link was made. Product quality declined steadily. The experimental test plan was not followed.

A Dual Module (VIW and SIW to SPW) was run for 11 days. The intent was to inject equally into SIW and VIW, but this did not go smoothly. Injection alternated back and forth, trying variously to rekindle old cavities and solve plugging problems that were thought to be associated with a pool of ash slag covering the injection point(s).

Module 1 (SIW to SPW) had begun running well and was used for the last 30 days of the operation.

In total, there were 65 days of oxygen-steam forward burn operation, consuming 4,686 Mg during Module 1 (SIW injection), 1,351 Mg during Module 2 (VIW injection), and 1,730 Mg during Dual Module operations. The average product gas heating value was 12.8 MJ/Nm<sup>3</sup>, with Module 1 at 13.3 MJ/Nm<sup>3</sup>.

Gas losses were negligible and no water contamination was zero or negligible. A process well (VLW) had a hole burned through its casing 55 meters below the surface during ignition or linking operations, but apparently it did not leak product gas. Instrumentation wells that are intercepted by the burn cavity will become pressurized when they are thermally consumed, and this must continue to be designed for safety.

Conclusions include the following: Ignition and reverse-burn linking and even connecting of near-miss wells do not always go easily. Once linked, a steeply dipping bed process can be run with a low injection point and a borehole and/or reverse link extending from it upwards to a production well. Steeply dipping bed UCG can produce excellent quality product gas, probably because of the thermal efficiency of the “fire pit” or moving packed bed nature of the process. The burn cavity tends strongly to go more up than sideways.

## 4.6 Pricetown (METC)

### 4.6.1 Description

Morgantown Energy Technology Center (METC) conducted a field test in Pricetown, West Virginia during 1979. Good reports on this field test include Schrider and Wasson (1981), Liberatore and Wilson (1982) and Agarwal et al. (1981).

The well-known Pittsburgh coal seam was the target. At this location, it was 1.8 m thick, and nominally 270 meters deep (variously reported between 259 and 274 meters). Analyses showed a high-volatile

bituminous A coal that swells and agglomerates. The proximate analysis of one core was 48.4% fixed carbon, 38.1% volatile matter, 12.1% ash, and 1.4% moisture, with no heating value in the reports reviewed.

Three vertical process wells were drilled and completed into the lower third of the seam. They were in a line, with 18 meters between wells PI-1 and PI-2, and 12 meters between wells PI-2 and PI-3. Four instrument wells (thermocouple and gas sampling) and two hydrology wells were completed and grouted down to the seam.

The middle PI-2 well was ignited on the second ignition try, using a burlap bag of charcoal briquets and three electric squib/fuse assemblies. A reverse-burn linked the 12 meters from PI-2 to PI-3 in less than 6 days, by injecting air into PI-3 using pressures over 58 bar gage (32 bar more than a rough estimate of hydrostatic pressure). But this reverse-burn channel had insufficient permeability to support gasification. An additional 100 days were spent on linking between PI-2 and PI-1 and trying to enhance the permeabilities of the links using various combinations of air injection locations, pressures, and flow-rates. These reverse-burns and enhancement efforts completely gasified 67 Mg of coal and another 322 Mg were pyrolyzed only. The gas produced during this period reflected the large ratio of pyrolysis to gasification, having a very high methane content and heating values between 6.8 and 10.9 MJ/Nm<sup>3</sup>.

Finally, a proper gasification phase was started, but it only lasted 12 days. A series of flow resistances were encountered underground and/or in production wells. Injection locations were moved around, with mixed success, followed by more flow resistance.

The test was stopped after a rupture in the casing of the PI-2 well occurred, pressurizing the aquifer at a depth of 62 meters with product gas.

From METC reports, during the 12 days of forward gasification phase, 175 Mg of coal were completely gasified and another 75 Mg were pyrolyzed only, totaling 250 Mg of coal, and the product gas had a heating value of 4.8 MJ/Nm<sup>3</sup>. From Cena and Thorsness' database calculations, during 17 days of forward gasification phase, 460 Mg of coal were gasified or pyrolyzed, and the product gas had a heating value of 5.9 MJ/Nm<sup>3</sup>.

#### **4.6.2 Observations and conclusions:**

The over-riding major conclusion is that trying to do UCG in swelling agglomerating coals is problematic. UCG capabilities must improve considerably before trying to tackle these difficult coals again. Drilled boreholes, probably of large diameter, are expected to work better than reverse-burns for creating links.

The reverse-burns in this coal drew a combustion front or finger from the ignited well to the producing well at linear rates between 1.2 and 2.0 meters per day. But this did not produce a sufficiently conductive link to support gasification, and it took two months of link-enhancement activities to achieve sufficiently conductive pathways between the wells.

The reverse-burn linking phases used pressures that greatly exceeded the surrounding water pressures making it very likely that gas and its contaminants were forced into the deep formation during that period. Flow restrictions kept occurring, either in the coal or in the pipes. These were attributed to the swelling agglomerating coal and the condensation of tars.

A casing rupture in a production well provides a pathway for contamination of shallower aquifers. Water quality tests in that aquifer soon after the casing leak showed minor changes, but within 2 weeks, aquifer quality had returned to pre-burn levels. Somehow the contaminants carried into the aquifer by the product gas did not go far (condensing, dissolving, adsorbing), and/or the escaping gas fingered in a way that

avoided the sampling wells, and/or far-field clean water re-invaded the sampling-well locations once the pressure was dropped back down.

## 4.7 The Centralia series of field tests (LLNL)

### 4.7.1 Summary and site description

The Large Block tests (LBK) and the Partial Seam CRIP test (PSC) were conducted by LLNL near Centralia in southwestern Washington. They were done in cooperation with the Washington Irrigation & Development Company (WIDCO), under the sponsorship of DOE and GRI. These tests are sometimes named “WIDCO”, or “Tono Basin” in some references; the LLNL team always used “Centralia.”

These tests were unique in that they were conducted at an exposed face or “high-wall” of a coal seam at a mine on the side of a hill. This allowed post-burn excavation of the cavities. The Big Dirty seam was being mined at WIDCO’s Bucoda field. The exposed seam face was part way up a hillside, with cut terraces below the face and the natural hill slope and hill-top above it. The terraces were used to drill into the seam and for piping, instrumentation, and support equipment. Figure 14 is a cutaway sketch of the site, showing the configuration of the PSC test. The seam dips down away from the exposed face at 13-15 degrees. From the coal face to the far end of the processing boreholes of the PSC test was about 275 meters. The vertical distance from the hilltop down to the seam at this location was about 63 meters.

The motivation and goals for these tests were to move from the high-permeability and wet weak overburden Hoe Creek site to a geologic setting more favorable for UCG, explore the effect of oxygen-steam ratio and flow rate on performance, excavate UCG cavities to learn more about their development and nature, and, most importantly, to test out LLNL’s recently conceived and developed CRIP method and hardware.

The Late Eocene coal was subbituminous and contained considerable ash in the form of stringers. The as-received analyses for the LBK and PSC tests, respectively, were: 35% & 27.5% fixed carbon, 29% & 34.4% volatile matter, 22% & 17.3% moisture, and 14% & 20.8% ash. Various seam thicknesses are given in different reports, varying between 5.5 and 11 meters. These can be reconciled by supposing that the top 5.5-8 meters of the 11-meter seam were highest quality and targeted for these experiments. The unit above the coal was a carbonaceous shale, and above that was a siltstone. All three zones had low permeabilities.

The Large Block tests were originally conceived as a set of tests in large, isolated blocks of coal. However, they were actually conducted in adjacent locations next to each other at this exposed coal seam face. There were five similar small-scale oxygen-steam tests. Each of the tests lasted 3 to 5 days and consumed about 20 tons of coal. The fifth of these (LBK-1) included the first test in the field of the CRIP process, proving that the feasibility of the maneuver to re-locate the injection point and ignite the burn there. After the tests, the cavities were excavated and inspected.

The Partial Seam CRIP test was a full-scale oxygen-steam field test, of similar magnitude to most of the others in the past decade. It was the first full-scale field test to use CRIP, and it successfully demonstrated its feasibility. After the test, the cavity was excavated and inspected to learn about its shape, nature, and contents.

### 4.7.2 Recommended References

Hill and Thorsness (1983) give the best summary of the Large Block tests. Far more details are provided in Hill and Thorsness (1982), Hill et al. (1984a), and (Ramirez et al., 1982). Three reports with highly overlapping content describe the Partial Seam CRIP test (Hill et al. 1984b and Cena et al. 1984a,b). Both

Large Block and Partial Seam tests are summarized briefly by Stephens et al. (1985) and Thorsness and Britten (1989c).

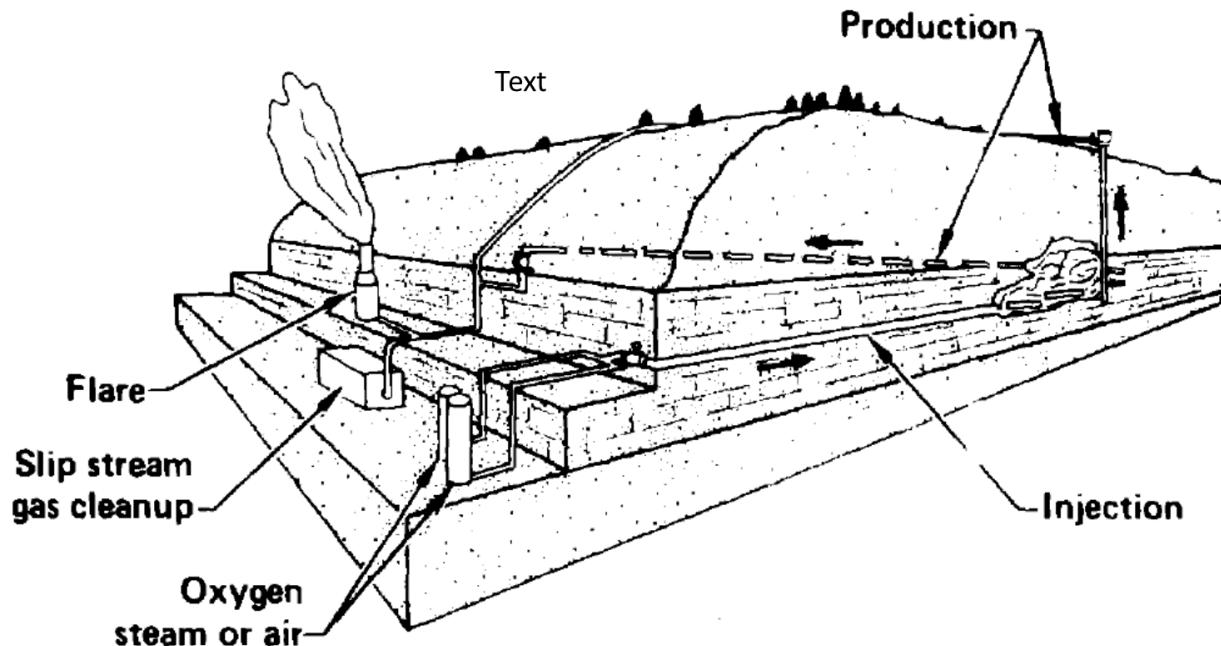


Figure 14. Sketch of the WIDCO mine site at Centralia showing the configuration of the Partial Seam CRIP test. The terraces on the left are real. The right face of the figure is a cut-away cross-section. (Hill et al., 1984)

#### 4.7.3 Large Block (LBK) tests

##### 4.7.3.1 Wells, links, and summary of operations

Confusingly, the five Large Block test names are ordered in reverse chronological order. LBK5 was done first and LBK1 was last. LBK5-2 were constructed identically. A 13-cm diameter injection borehole was drilled about 30 meters into the coal seam from the face, going down-dip parallel to and about 7.6 meters below the roof of the seam. A stainless steel liner was inserted into each of these about 12 meters, leaving the distal ~18 meters of the borehole open. A vertical production well was drilled and completed about 24 meters down from the ground surface above, to intersect the injection borehole near its end. For LBK1, the injection borehole was intentionally higher in the seam (1.8 meters below the top) to assure an opportunity for excavation to witness cavity-roof interaction, reamed out to 20 cm diameter, and the liner was inserted 19 meters to allow for the CRIP maneuver to ignite the second cavity 7 meters upstream from the first one. Many instrument wells were placed around the process wells.

Ignition for each test successfully used a sequence of enriched oxygen, silane, and propane into an igniter tool within the liner of the injection well. Each of the cavities were allowed to burn for the

same amount of injected oxygen moles and terminated when about 25 m<sup>3</sup> of coal was consumed. An experimental schedule varied the oxygen-steam ratios and injection rates from test to test. There were significant operational difficulties. Most tests suffered from high pressure drop because coal, char, and ash rubble filled the borehole. In two of the tests, reverse burns were tried to open up the channel but without success. The pressure drop caused much of the product gas to flow out the uncemented injection borehole, outside the injection liner. During an experiment with a high oxygen ratio, the high temperatures caused molten ash slag to pool around and plug the injection point.

Following the initial 25-m<sup>3</sup> phase of LBK1, a CRIP maneuver was performed. The igniter tool was moved to a position 7.3 m upstream (towards the coal face) from the initial ignition point at the end of the original liner and used successfully to burn off the liner and ignite the coal at this new location. The burn was operated at this second injection point for a full day, gasifying a new cavity around this point, before ending the experiment. Product gas flowed through the first cavity and out the borehole link channel to the vertical production well, making this a linear CRIP operation.

#### **4.7.3.2 Cavity growth and geometry**

The cavities were excavated carefully after the tests and manually examined, informing by direct observation the knowledge base on the nature and shape of early-phase UCG cavities (Figure 15). In this context, a cavity is defined as that region within the coal seam in which drying, pyrolysis, and/or combustion occurred, not necessarily a void.

Cavity growth and nature was insensitive to the experimental parameters of injection composition and rate, except that the high-oxygen injection caused slag to plug the injection point. Figure 16 shows a typical cross-section in the combustion zone. Height-to-width ratio was typically 1.3-1.7 to 1. Most of the cavity volume was filled with rubble consisting of dried coal, char, ash, and some slag. Ash and slag are confined to the bottom. Toward the production well, the volume is entirely dried coal and char rubble extending upward from the original borehole.

The “Interpretation” section of Hill et al (1984a) provides a detailed qualitative discussion of the UCG and cavity-growth phenomena that would be consistent with these observations.



**Figure 15. All five of the Centralia Large Block tests were excavated, inspected, described, and documented. This advanced an understanding of the rubble-filled nature of UCG cavities. (LLNL photo)**

#### **4.7.3.3 Performance data**

The performance was insensitive to changes in oxygen-steam ratio or flow rate. All five tests produced gas with heating value between 10.3 and 11.2 MJ/Nm<sup>3</sup>. Operational issues and interaction with the environment had a greater impact on operations.

#### **4.7.3.4 Observations and conclusions**

The successful execution of the first CRIP maneuver in the field demonstrated its technical feasibility, and operation in linear mode.

The excavation of the small cavities provided a good look at the nature of the initial phase of cavity development in a horizontally linked system. The burn cavities were found to grow upward faster than outward and be mostly filled with rubble, dried coal, char, ash, and slag. This gave the team the first indication that the rubble and the residual ash after complete coal consumption might play a key role in distributing injected reactants in a developing UCG cavity. (Thorsness and Britten, 1989c). The initial borehole exit channel toward the production well had become filled with particulate char and dry coal, which extended up a considerable distance. Significant coal consumption took place backwards in the direction of the coal face. The forward borehole had filled with rubble and a fraction of the gas flowed backwards in the injection borehole between the uncemented injection liner and the coal.

During one of the tests, an injection point had plugged during the period of highest oxygen concentration in the injected gas. The excavation inspection revealed this to be plugged with mineral

slag. This remains the best hypothesis for the plugging of the injection point that happened previously in the Hoe Creek III test.

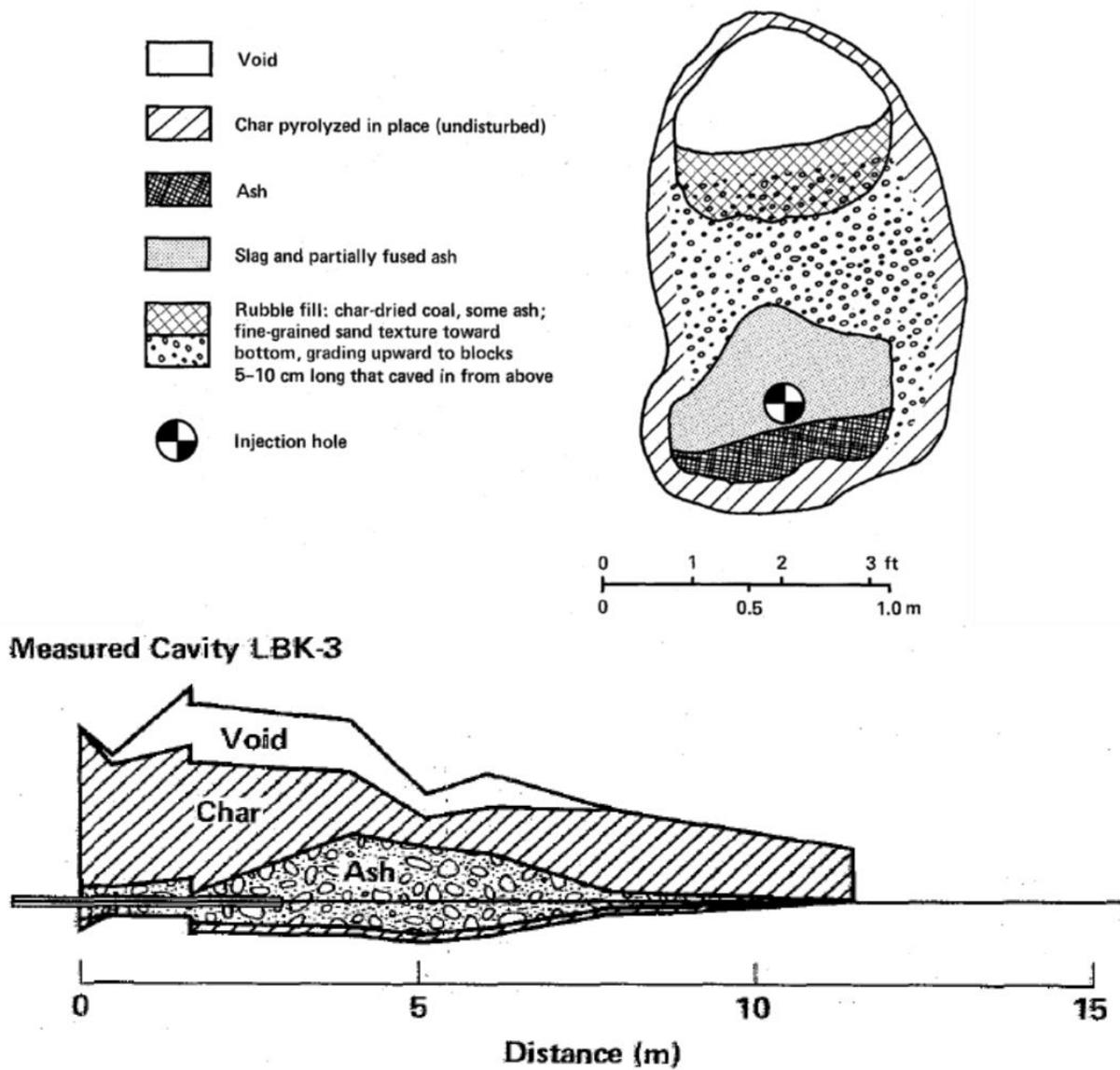


Figure 16. Vertical cross-section of a typical Large Block test cavity, transverse to the injection well axis; and a cross-section of LBK3 along the injection well axis. (Hill et al., 1984a)

#### 4.7.4 Partial Seam CRIP (PSC) test

##### 4.7.4.1 Wells, links, and summary of operations

The Partial Seam CRIP test took place at the high-wall coal face that was left after excavating the Large Block tests. As shown in Figure 14 above and Figure 17 below, the 17-cm diameter injection borehole/well was drilled from the exposed coal face near the bottom of the seam, running into the coal downdip for 275 meters. The first 192 meters was reamed out to a diameter of 30 cm, and cased to that point with 20-cm casing. An inner 14-cm stainless steel liner was run through the casing and further down the borehole to a distance of 253 meters, 23 meters away from the vertical production well, PRD-2. The elevation of this injection well in the vicinity of the initial and CRIP cavities was estimated at 4.3 meters below the top of the seam. PRD-2 was completed to about 6 meters below the top of the seam, about 69 meters below the ground surface.

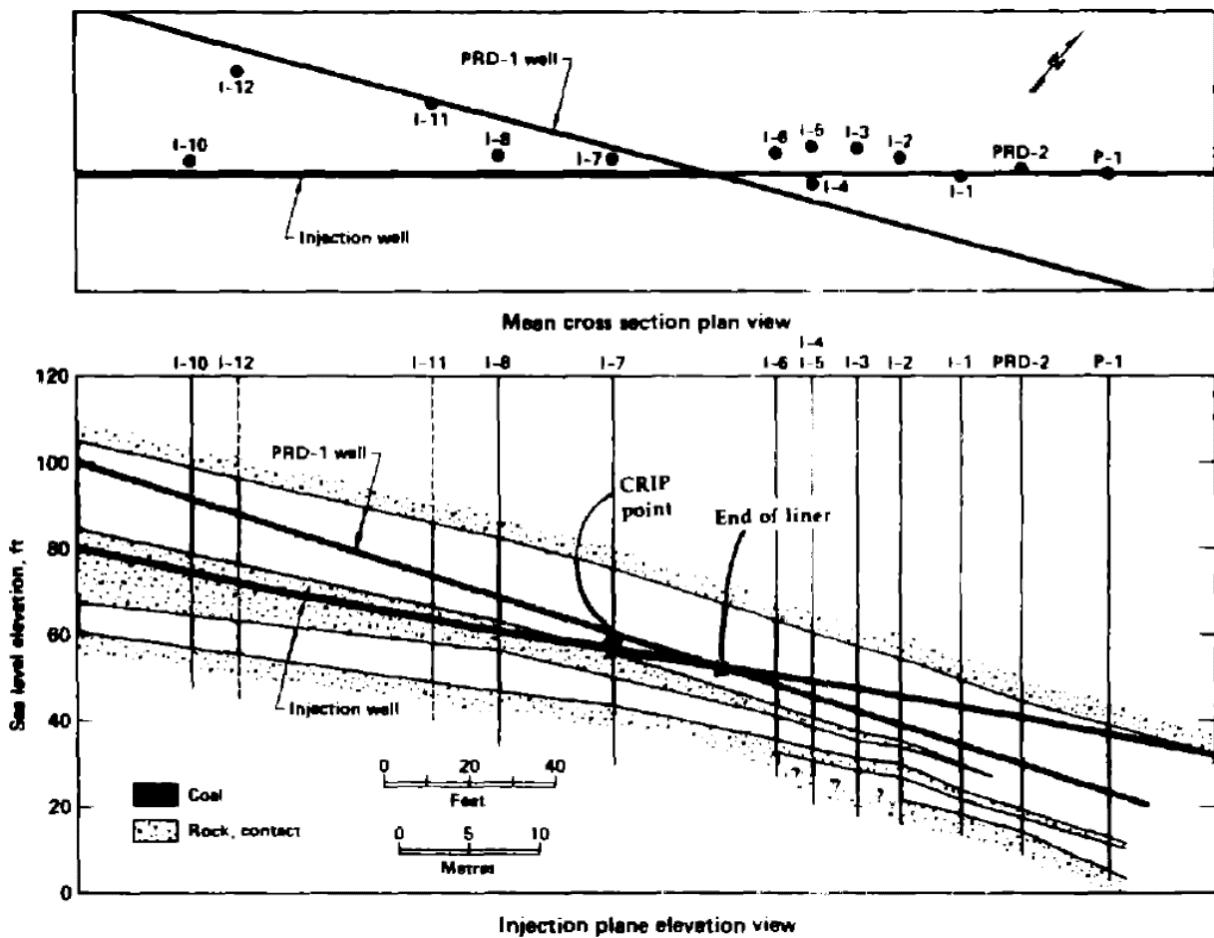


Figure 17. Plan (top) and elevation (bottom) views of the PSC process and instrument wells. The burn was started at the end of the injection-well liner, and that was the injection point until the CRIP maneuver burned a hole in the liner at the CRIP point, igniting and injecting there. Initial production was out of vertical well PRD-2, and later through the slant production well, PRD-1. (Hill, et al., 1984b)

The slant production borehole, PRD-1, was at a 15° angle to the injection well, in plan view. PRD-1 began above the seam and stayed in overburden until entering the coal seam about 60 meters before the end of the liner, descending through the seam to passing near the end of the injection-well liner. It was 250 m long. PRD-1 was drilled at 17 cm diameter and reamed to 22 cm. The first 195 m was reamed wider and cased with 24-cm casing to a distance from PRD-2 that is not in the reports, possibly near where I-11 intersects PRD-1 in the elevation view of Figure 17.

The intersection between the injection borehole and PRD-2 was close enough that no reverse-burn connection had to be made. The connection between PRD-1 and the injection well was made by the growth of the cavity while producing out of PRD-2.

In addition to many thermocouple and time-domain-reflectometry wells, Sandia National Lab fielded a CSAMT (Controlled Source Audio-frequency Magnetotelluric Technique) system to try to delineate the cavity boundaries. (Bartel et al., 1983)

A 1.2-cm diameter stainless steel tube inside the liner fed the igniter tool, initially located at the end of the liner. Pyrophoric silane gas was used to ignite a propane flame downhole which ignited the coal. The igniter was pulled 7.6 meters back from the end of the injection liner. After a day of air injection for training, the injection was switched to oxygen-steam. After 8 days of production through PRD-2, the cavity had connected PRD-1 and product flow was switched to PRD-1 in only 2 hours by opening PRD-1 and throttling down PRD-2. The product gas quality improved after switching over.

After 12 days of forward burn, a CRIP maneuver was performed at the igniter's location. A nearby thermocouple confirmed that the liner had been burned through, the coal had ignited, and a new forward burn cavity had begun, and flows were ramped up. The igniter became stuck in this place and could not be retracted, precluding a second CRIP maneuver later. The operations schedule shows that the CRIP maneuver occurred in the middle of 3 days of air injection, which may have been intentional or may have been due to one of several power-loss and steam-boiler problem events which always forced a period of air injection.

Eight days after the CRIP maneuver a major underground roof collapse occurred. Usually the cavity grew upward by small spalls and fractures of roof material into rubble. The top of the collapse block was 5.5 meters above the coal seam; the bottom of the collapse block is unknown. This event caused a reduction in the gas heating value which never recovered. Gasification continued smoothly, including a recovery following a period of very low flow during a procedure. The 30-day time limit was reached and the operation shut down.

Operational difficulties included frequent power outages and steam boiler failures, plugging of a valve that led to blowing a rupture disk and losing product-line pressure, and imperfect drilling trajectories.

Post-burn coring was done to delineate and characterize the cavity. Later, the mine operators began to actively mine coal there, allowing excavation of the two burn cavities and the outflow channel.

#### 4.7.4.2 Cavity geometry and nature

Figure 18 shows the exposed coal face where the cavity was relatively large, and a sketch of the cavity based on observations and characterization of thermally-modified minerals. The sidewalls of the ~20-meter-wide cavity were bowl-shaped (concave up) near the bottom, becoming largely vertical, and extending far up into the overburden, higher than wide. Observations were conclusive that the rubble was in place during the test and not a result of subsequent caving.

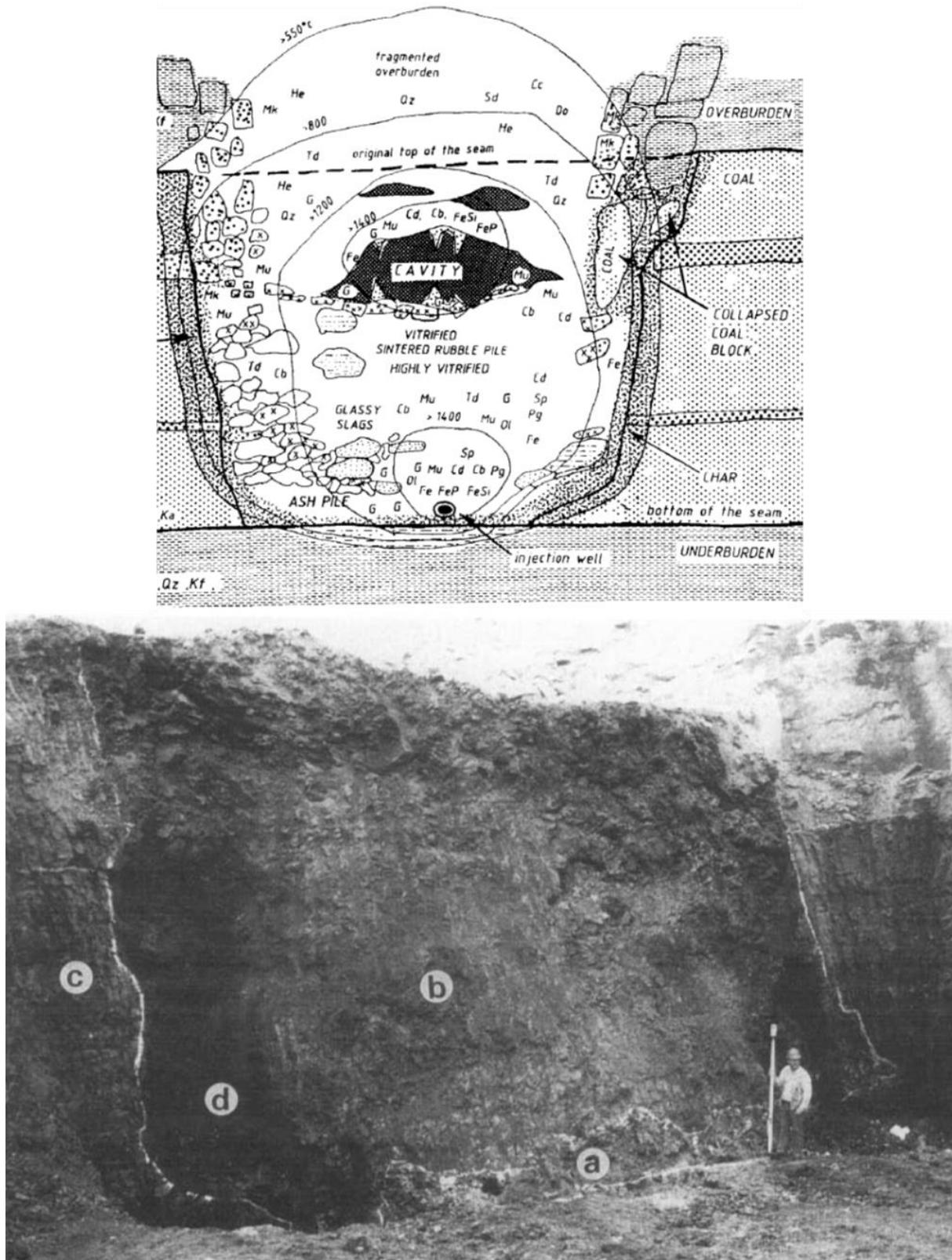


Figure 18. The Partial Seam CRIP field test, done at the exposed face of a coal seam, was excavated, inspected, sampled, and analyzed to learn the nature of the rubble-filled cavity. (c) is virgin coal, (d) is char, (a) is ash slag, and (b) is thermally-affected overburden rubble. (Kühnel et al. 1993)

Drill-backs at the Hoe Creek and Hanna tests, and the recent excavation of the Large Block tests had previously found a “cavity” full of ash, slag, char, coal, and rubblized/broken overburden, and strong indications that the outflow production borehole that had expanded up and out into a “V” shape full of char and dried coal rubble.

Any remaining notion that UCG could be pictured as an open cavity and a rock ceiling was dispelled by the excavation of the Partial Seam CRIP test. The excavation of the PSC test found the “cavity” to be full of ash, slag, char, dried coal, and rubblized overburden, with a few gaps. “The PSC excavation revealed an upward V-shaped outflow channel filled with char. The cavity region itself consisted of a rubble-filled region with near-vertical sides. The bottom of the cavity was coincident with the location of the originally drilled injection channel.” (Thorsness and Britten, 1989c).

An interesting study of the mineral pyrometamorphism that took place allowed reconstruction of the maximum temperatures seen in various regions (Kühnel et al., 1993). This paper and earlier work referenced there-in contain photographs of the excavation. The isotherms shown in Figure 4 of this paper show the hottest region within a few meters of the injection well at  $>1400$  C (consistent with mineral studies from other UCG field tests), the former seam-overburden plane between 800 C near the cavity perimeter and 1200 C at the centerline, and the  $>550$  C contour reaching 3-4 meters above the former top of the seam into the fragmented overburden. Even a simple picture of rubblized rock is belied by their description of “stalactites and stalagmites” found in half-meter voids near the top of the former coal seam, “Melt derived from illite-rich clay, with a viscosity at 1400 C similar to that of honey, had trickled down on the glowing pile of mullite-rich ash derived from the kaolinite intercalations in the coal seam. This resulted in the formation of a breccia ...”

#### **4.7.4.3 Performance data**

Discernable amongst the “noise” associated with mechanical failures, three distinct gasification periods of oxygen-steam injection were observed. The initial period, in which the vertical production well was in use, yielded a dry-gas heating value of 9.8 MJ/Nm<sup>3</sup>. This was followed by a period of considerably higher gas quality, 11.7 MJ/Nm<sup>3</sup>., which resulted from the switch to the lateral production well and the CRIP maneuver. The final period began when a large-scale underground roof fall occurred, with a typical gas heating value of only 8.7 MJ/Nm<sup>3</sup>.

Approximately 610 Mg of coal were gasified with the first cavity and 1210 Mg during the second (following the CRIP maneuver), for a total of 1810 Mg, or about 2400 Mg if coal converted only to char is counted.

Gas losses averaged 17%, based on tracer data. They did not correlate with either cavity size or pressure, but did drop after switching the production from PRD-2 to the lateral PRD-1.

Increasing operating pressure was ineffectual for controlling water influx. Water influx did correlate with switching production to PRD-1, possibly because the low-lying PRD-2 collected water which evaporated when production was there, but sat when production was out the higher PRD-1. The roof collapse event produced a temporary increase in water influx but no lasting increase.

#### **4.7.4.4 Observations and conclusions**

The PSC test demonstrated that the CRIP process was technically feasible on a full-scale system. The CRIP maneuver initiated a new gasification cavity at a new location. It also indicated that the desired

increase on product quality could be effected by initiation of a new cavity. (However, operational and other difficulties clouded the issue as to the exact effectiveness of the CRIP operation).

The CRIP operation was in “parallel” configuration. The switch from “linear” to “parallel” configuration corresponded to an increase in product gas quality (even before the CRIP maneuver), but some indications were that this increase was transitory.

Post-burn excavation yielded an unambiguous picture of the cavity shape and its contents. It is not empty but full of slag, ash, char, dried coal, and thermally-altered overburden rubble. The cavity shape in cross-section had a bowl-shaped bottom, steep sides, and was taller than wide. Mineralogical examination yielded a picture of the maximum temperature field in and near the cavity. The outflow channel for product gas flow, initially a borehole, grew up and out to become an upward “V” shape full of char and dried coal rubble.

## 4.8 Rocky Mountain 1 (DOE Consortium)

### 4.8.1 Site description

The Rocky Mountain 1 test (RM1) (Figure 19) was conducted several hundred meters east southeast of the Hanna tests (see Figure 2). Its geology and coal was described in Section 4.2.3.



**Figure 19. The Rocky Mountain 1 test took place near the old Hanna Wyoming site from November 1987 to February 1988. (LLNL photo)**

The pre-burn hydrostatic pressure at the ELW location in the middle of the seam was 104 meters of water, or about 10 bar gage; the seam at the CRIP location is about 10 meters higher, making that hydrostatic pre-burn pressure about 9 bar gage. The natural hydrologic gradient and flow is to the NNW.

The top of the seam had fractures and a fairly high permeability, averaging over 100 mD. The permeability, especially the relative permeability for gas flow, may have inadvertently been enhanced during the preparation phase when high gas pressures were used to assess air acceptance and create short reverse-burn connection links between the drilled boreholes and wells that missed each other by 1-3 meters.

Previous characterization of the site suggested that the modules would sufficiently far apart to be isolated from each other. But during the preparatory testing it was found that there was some hydrological interaction between the two modules. Again, this communication may have been enhanced during the high-pressure reverse-burn connections. In theory, the 10-meter difference in elevation (and hence in surrounding groundwater pressure) could be accommodated by always operating the ELW cavity at about 1 bar higher pressure than the CRIP cavity, but that was not so easy in practice given engineering constraints.

#### 4.8.2 Summary

Rocky Mountain 1 (RM1) proved to be the largest, most successful, and final test of the U.S. UCG program. It was organized by the DOE and cost-shared 50/50 with industry. The main high-level coordination came from GRI. Stearns-Rogers Engineering (United Engineers) was the primary engineering outfit and prime contractor. Other participating organizations included Amoco, EPRI, Union Pacific Minerals, Gulf, and Energy International, LLNL, WRI, and others. The technical decision-making board was led by Gulf / Energy International's Burl Davis. WRI staff had technical roles, especially in geology and environmental areas. LLNL was responsible for the data acquisition and control system, training operators, and had a substantial role in real-time operational decision making, in addition to CRIP operations. The site in the Hanna basin made sense because of familiarity and extent of previous characterization, the good performance of the nearby Hanna test series', and many other favorable attributes. The original test plan had only the Extended Linked Well (ELW) module. The Controlled Retracting Injection Point (CRIP) module was added after persistent advocacy by the Livermore contingent (Davis, 2011).

The well configuration of the two modules is shown in Figure 20. More detailed well sketches and the injection, production, and burn details are given below separately for each module. Initial drilling and site construction began in the spring of 1986. The modules were ignited, started up, stabilized, and switched to the main phase of oxygen-steam gasification in late November 1987, and run continuously until being shut down in mid January (ELW) and late February 1988 (CRIP). Perhaps to remind the U.S. team of its Russian predecessors, the weather provided blizzards, wind-chills to -36°C, and challenges with frozen equipment (Figure 21).

For the ELW module, the initial injection well was VI-1 with VI-2 being the planned second injection well. The ELW production well P-1 was cased to about 90 meters from VI-1 and open borehole the rest of the way. Produced gas was intended to flow through the open production borehole and into the cased portion of production well P-1. The ELW module ran fairly well, but its performance and duration were handicapped because the end points of the casing of its injection wells were incorrectly completed near the top of the seam instead of the bottom. It was not able to successfully switch injection to the second injection well, VI-2.

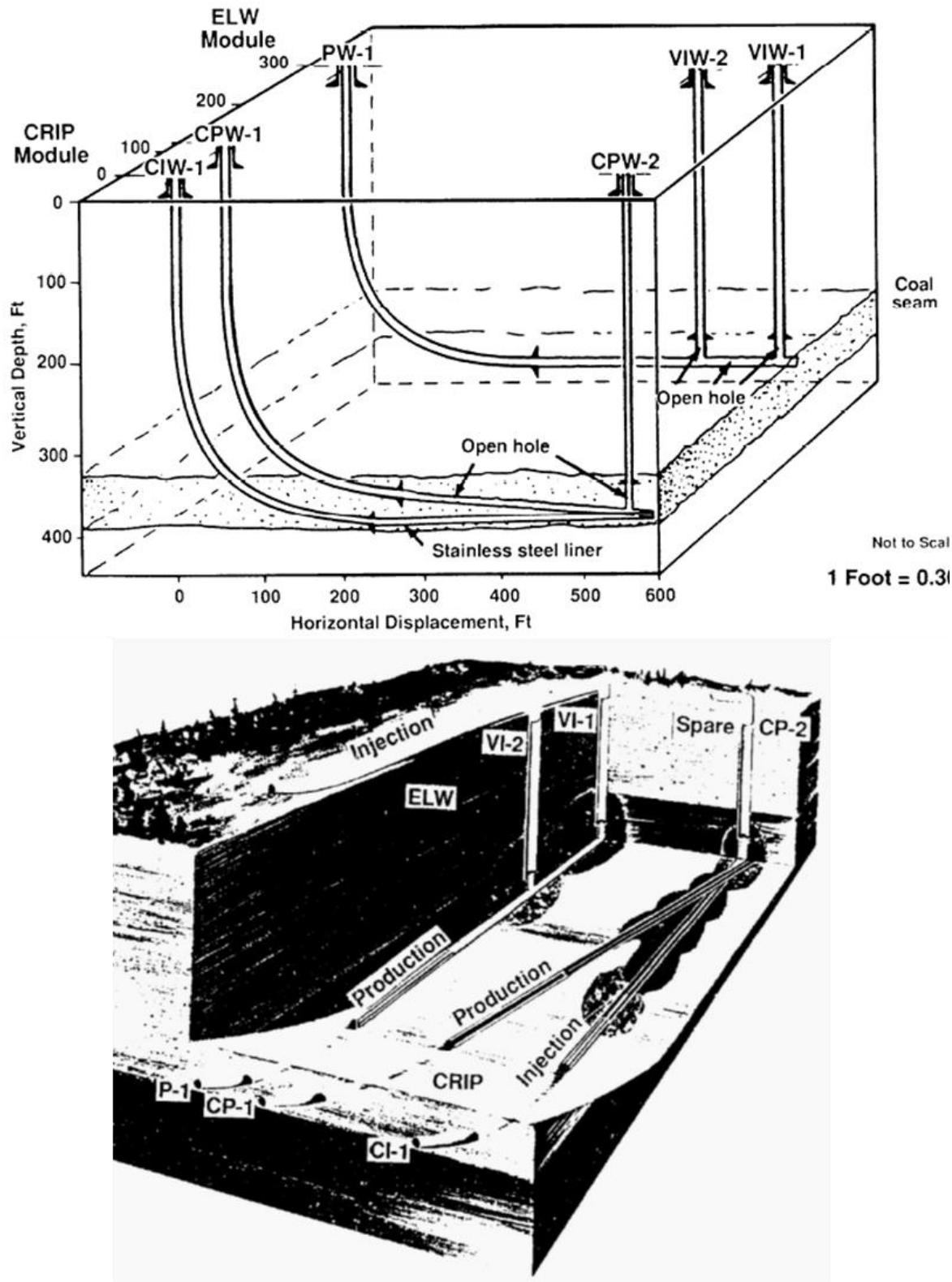
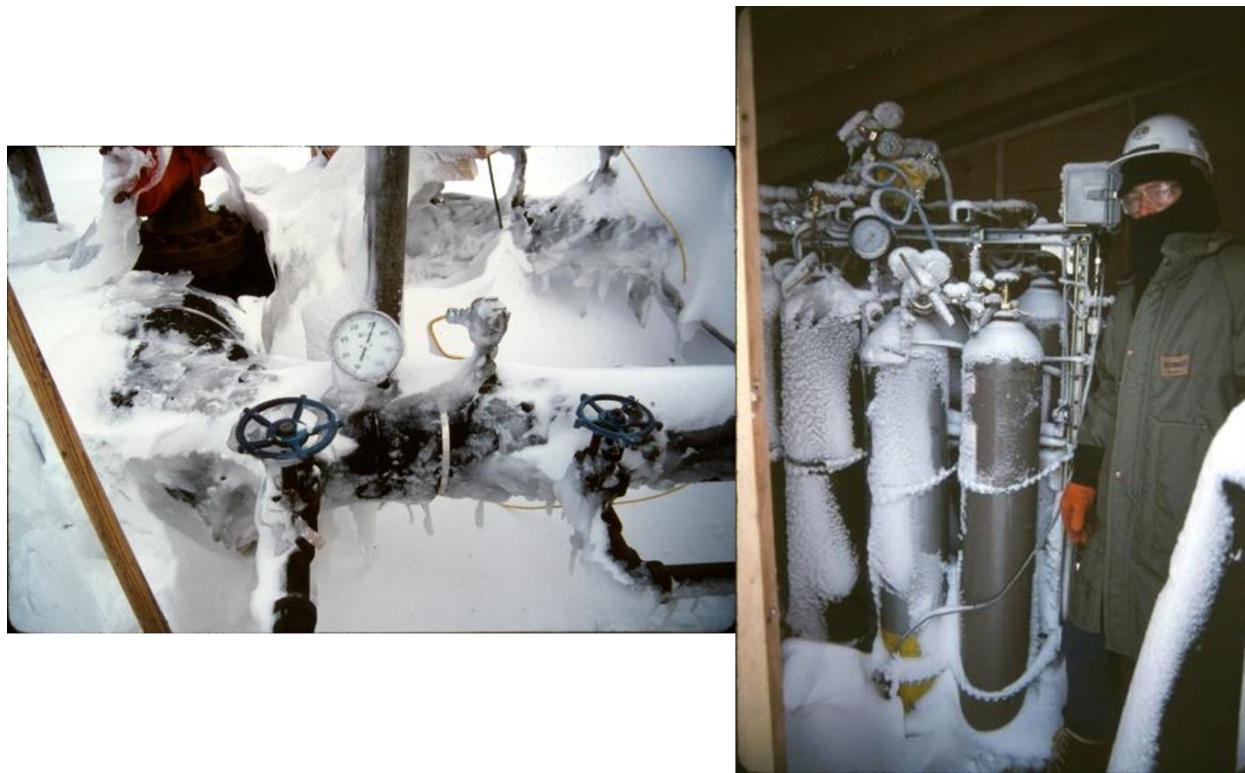


Figure 20. Rocky Mountain 1's process well layout for its side-by-side ELW and CRIP modules. The artist's cutaway shows the planned cavity sequences; both modules stopped one cavity short of what is shown, and the cavities in both modules extended up higher than shown into the overburden. (Thorsness and Britten, 1989a)



**Figure 21. Wyoming's winter weather repeatedly challenged American UCG field test operations, including the final Rocky Mountain 1 test. (LLNL photo)**

For CRIP, injection was always into the horizontal well CI-1. The injection point was initially at the end of the well casing within about 4 meters of CP-2, but was periodically moved upstream (west) about 18 meters at a time by a CRIP maneuver. The burn was initiated using vertical well CP-2 for production but then was soon switched to the CP-1 production well which was cased to about 90 meters from CP-2 and open borehole the rest of the way to its intersection with CI-1 and CP-2. The CRIP module ran very well, produced high-quality gas, and had no serious problems over 93 days of forward-burn gasification. Four successive cavities were operated, using three CRIP maneuvers to create new ones.

A post-burn drilling, coring, and logging program was done in the years after the test. This was used, along with downhole thermocouple data and material balance information obtained during the test, to delineate the cavity boundaries and extent of thermal alteration of surroundings, and describe the cavity contents. (Lindblom et al., 1990, superseded by Oliver et al., 1991).

Groundwater contamination received serious attention. The test was located in a clean area up-flow from the previously-contaminated Hanna field test sites. Groundwater quality measurements during operations exceeded the permit limits, due to escape of pyrolysis gas during the small reverse-burn connections that had to be made during start-up, when gas pressures exceeded the fluid formation of the surroundings (Beaver, 1988). The technical team had sufficient understanding, system monitoring information, and model calculations to persuade the regulators to agree to proposed adjustments and allow the test to proceed (Dennis, 2006). The Clean Cavern method of shut-down was done for the first time and it reduced the inventory and spread of contaminants (Boysen et al., 1990). Following groundwater remediation activities, the Wyoming Department of Environmental Quality deemed site reclamation a success in 2005 and released the project from further responsibilities.

### 4.8.3 Recommended references

There were many contemporary topical reports on the Rocky Mountain 1 (RM1) test, but no full-scope summaries. The Proceedings of the Thirteenth and Fourteenth Annual UCG Symposia (1987 and 1988) contain many of the reports on site description and plans, and early results and analyses, respectively. Many topical reports appeared in the years following. A chronology and cursory description of results is found in Bloomstran et al. (1988). Several papers by the LLNL group gave brief overviews and then analyzed various aspects of the test, with emphasis on the CRIP module (Thorsness et al., 1988; Cena et al., 1988a,b; and Britten and Thorsness, 1988). The effects of geology and hydrology on process results was described by Oliver (1988a). Boysen, et al. (1988 and 1990) gave good overviews of the test and described the post-burn venting, flushing, and cooling operations. Lindblom et al. (1990) and Oliver et al. (1991) described cavity mapping by post-burn corings. A series of detailed Gas Research Institute (GRI) reports documented the project after its completion, (c.f. United Engineers & Constructors, 1989, a 789-page “Summary Report on Operations”). A short “Final Technical Report” was issued in 2006 that gave an overview and emphasized environmental aspects. (Dennis, 2006).

### 4.8.4 CRIP Module

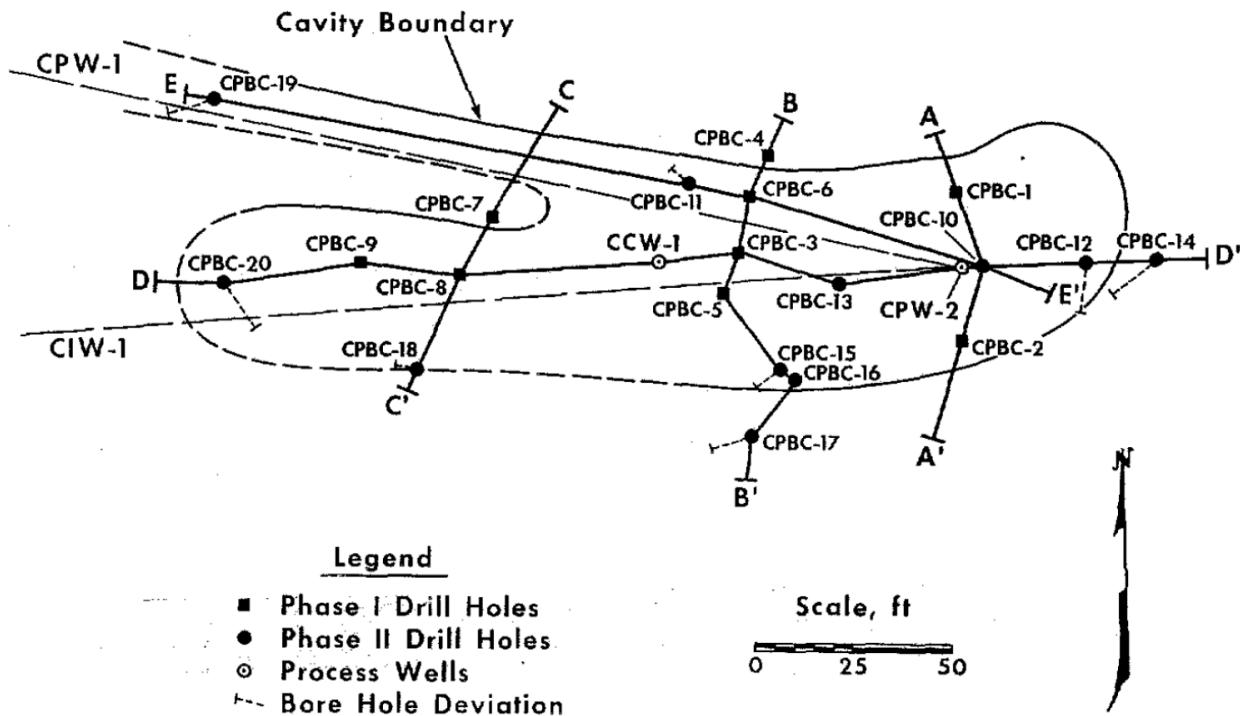
#### 4.8.4.1 Wells, links, and summary of operations

Figure 20 above provides a general schematic. Figure 22 is a plan view of the CRIP module, including locations of related cross-sectional views. The casing endpoint of the vertical production well (CPW-2) was near the bottom of the coal seam. The horizontal injection and production boreholes were in the bottom half of the seam, but apparently not in the bottom quarter of the seam (see Section 4.8.4.2). Such was the state of directional drilling navigation at the time. The injection well was cased to 4 meters from CPW-2. The horizontal production well’s casing started about 90 meters downstream (west) of CPW-2.

Ignition at the bottom of the vertical production well was accomplished by injecting pyrophoric silane followed by a methane/air mixture and took a several attempts and some modifications. Directional drilling technology at the time was such that the three boreholes/wells missed each other by about 3 meters. Reverse burns were used to make the short connections. The reverse-burn connections took a few days and used air injection pressures up to 12 bar gage, 3-6 bar above local hydrostatic. They were preceded by air acceptance testing that used air injection pressures up to 14 bar gage.

A three-day period of “stabilization” followed, when air was injected into CI-1, with production switched to the horizontal CP-1 production well. The injection rate was slowly increased to 1000 scfm, allowing development of the first CRIP cavity. Injection pressure (which is only slightly higher than cavity pressure) during this time was about 7 bar gage. Injection switched to an oxygen-steam mixture, the system stabilized, and baseline conditions set to 500 scfm oxygen, 1000 scfm steam, and 6.8 bar gage pressure.

Gasification continued with oxygen-steam injection for another 90 days during which the injection point was moved several times and the injection composition and rates were varied experimentally over limited ranges. The CRIP module operated for 93 days, including the air stabilization phase. Pressures during this period were slowly decreased to stay below surrounding hydrostatic pressures, guided by monitoring of the growing cone of depression around the module. In all, about 10.2 Mg of coal was gasified with an average gas heating value during the steam-oxygen period of 11.3 MJ/Nm<sup>3</sup>.



**Figure 22.** Rocky Mountain 1's CRIP module plan view, including the horizontal production borehole (CPW-1), horizontal injection well (CIW-1), vertical initiation and initial production well (CPW-2), and final cavity boundary (solid and short-dashed perimeter). The initial injection point (end of the CIW-1 casing/liner) was 4 meters in unknown direction from CPW-2. The production well (CPW-1) casing ends about 25 meters west of this figure. (Oliver et al., 1991)

The injection point was deliberately moved upstream (to the west) about 18 meters three times using a CRIP maneuver, after 41, 61, and 81 days of oxygen-steam injection. This was done by moving a silane-methane torch tool to the desired new injection point, using it to burn a hole in the injection well lining (casing) and ignite the surrounding coal, and then retracting it some distance upstream to protect it. CRIP is described more generally in Section 7.12. In addition to the CRIP maneuvers, the liner gradually receded upstream due to thermal attack. Figure 23 shows how the actual injection position changed through the experiment as a result of both gradual liner recession and maneuvers. The 9-meter move on day 78 was termed an “auto-CRIP” and probably resulted from thermal attack on the liner at an upstream point.

The CRIP module was shut down after 93 days of forward gasification because of schedule and budget. Post-burn Clean Cavern operations beginning with depressurization of both modules started after the CRIP module was done.

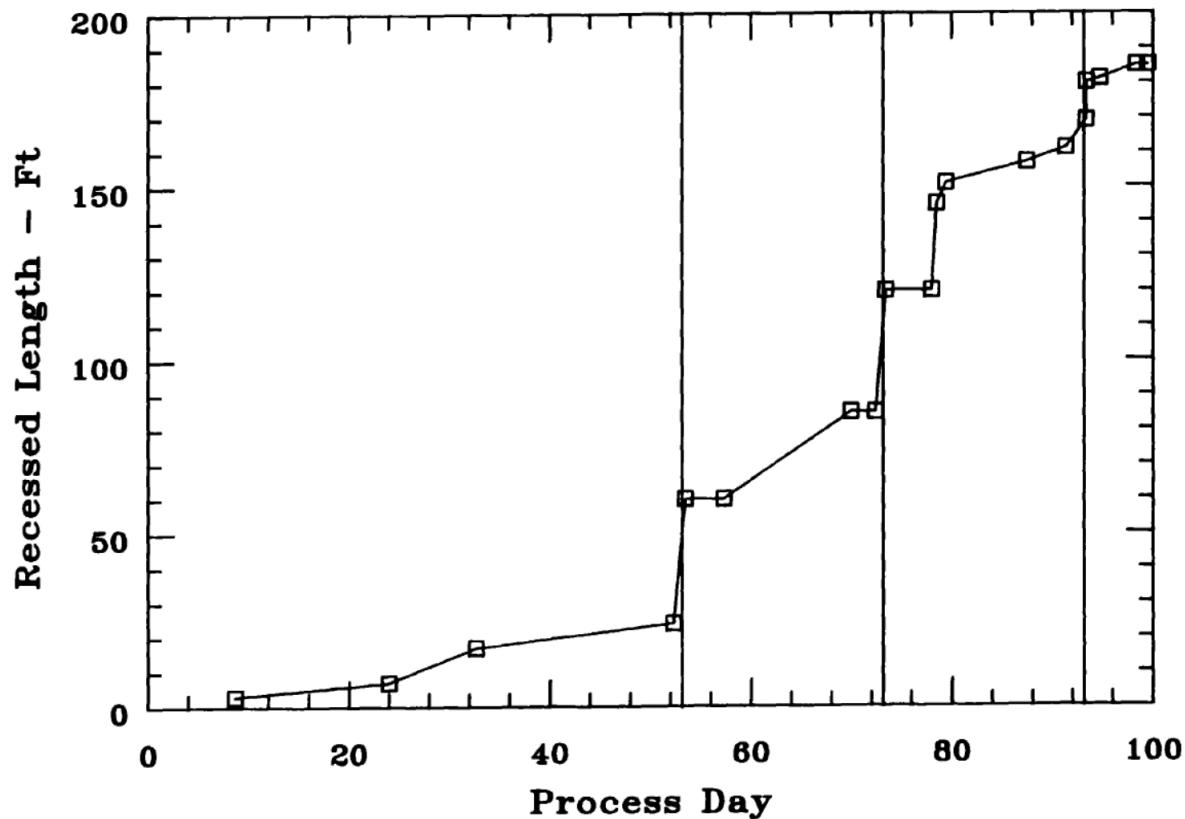
#### 4.8.4.2 Cavity growth and geometry

Figure 24 shows the movement of the injection points with time, and an early estimate (based on mass balance and limited thermocouple data but no post-burn drill-backs) of the cavity progression. (Cena et al., 1988b). The actual injection points are further west (left) than the intended CRIP points because of thermal attack recession. Note the large “auto-CRIP” jump in period C. The final estimated cavity shape is remarkably similar to the one drawn three years later (Figure 22 above) following extensive drill-backs. Figure 22 above also shows the cross-section locations.

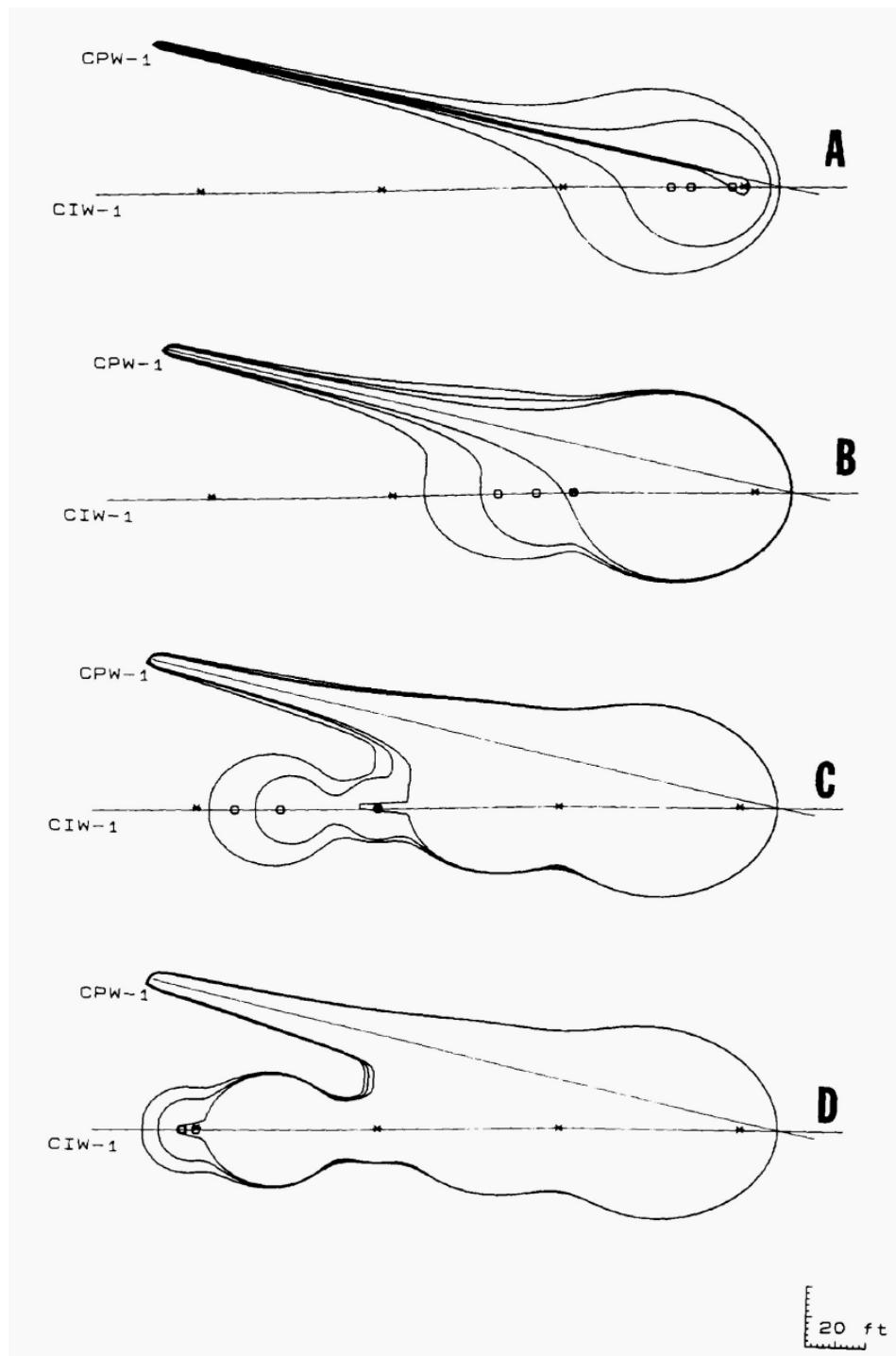
Figure 25 and Figure 26 show the lengthwise cross-sections of the final cavity, D-D' along the line of injection points, and E-E' along the production borehole. Figure 27, Figure 28, and Figure 29 show the three cross-sections perpendicular to the injection and production boreholes, all looking west. (Oliver et al., 1991 ). Cross-section C'-C is especially striking, showing the main burn cavity on the left and the exit channel on the right near the top of the seam. The cross-section along the production borehole is consistent with either that borehole being in the middle-top of the seam, or with over-ride in the exit path.

These cross-sections show that the thickness of the part of the seam that was utilized was about 6 meters, probably because that was the elevation of the imperfectly placed injection well and possibly production borehole. The results could be interpreted as what one might expect from a 6-meter seam in which the injection well was placed perfectly just above the bottom.

Where adequate time for growth had been allowed, the cavity width was roughly 18 meters or about 3 times the thickness of the gasified coal. The height of roof rock that fell into the cavity or was thermally altered was typically 1.5 to 2.0 times the height of the coal below it that was converted.



**Figure 23. Measured recession of the injection point by deliberate CRIP maneuvers (vertical lines and sharp changes) and thermal attack on the liner (gradual recession). The 9-meter move on day 78 was termed “auto-CRIP” and probably resulted from thermal attack at an upstream point. Oxygen-steam injection began on process day 12. (Cena et al., 1988b)**



**Figure 24. Early estimates of the cavity evolution with time, based on mass balance, downhole thermocouples, and knowledge of the injection point. Each figure represents one of the CRIP periods (between the vertical lines of Figure 23). Each period shows contours near the period's beginning, middle, and end. The location of the actual injection points at those three times are shown with open circles. X marks the intended CRIP injection locations at the beginning of each period. (Cena et al., 1988b)**

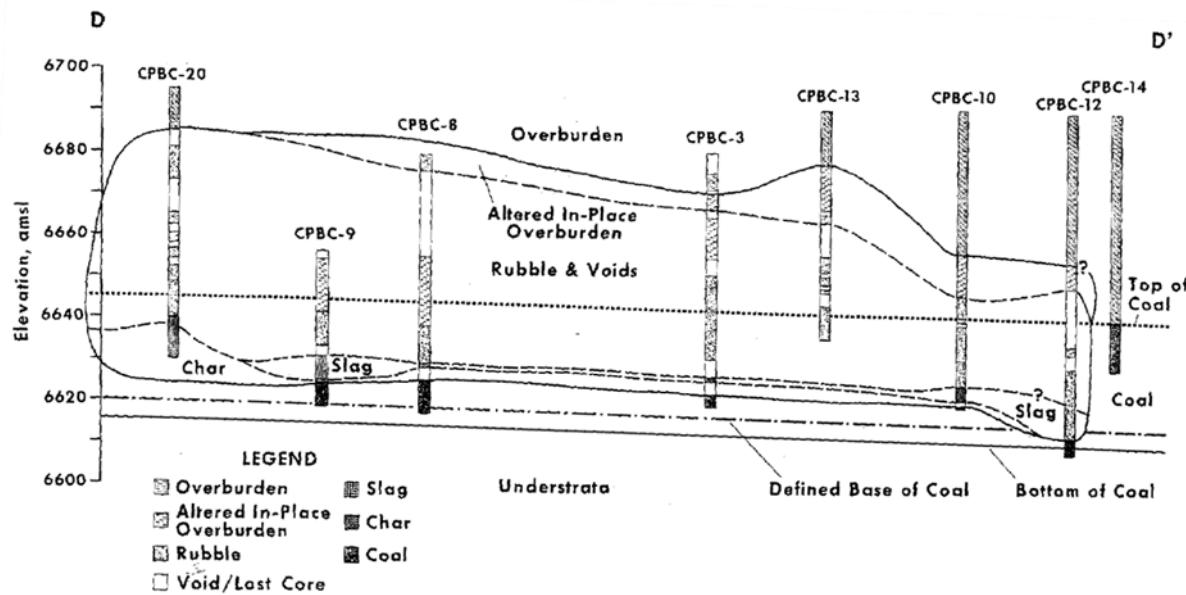


Figure 25. Rocky Mountain 1's CRIP module final cavity geometry looking north, cross-section D-D'. Figure 22 shows the corresponding plan view with a scale. (Oliver et al., 1991)

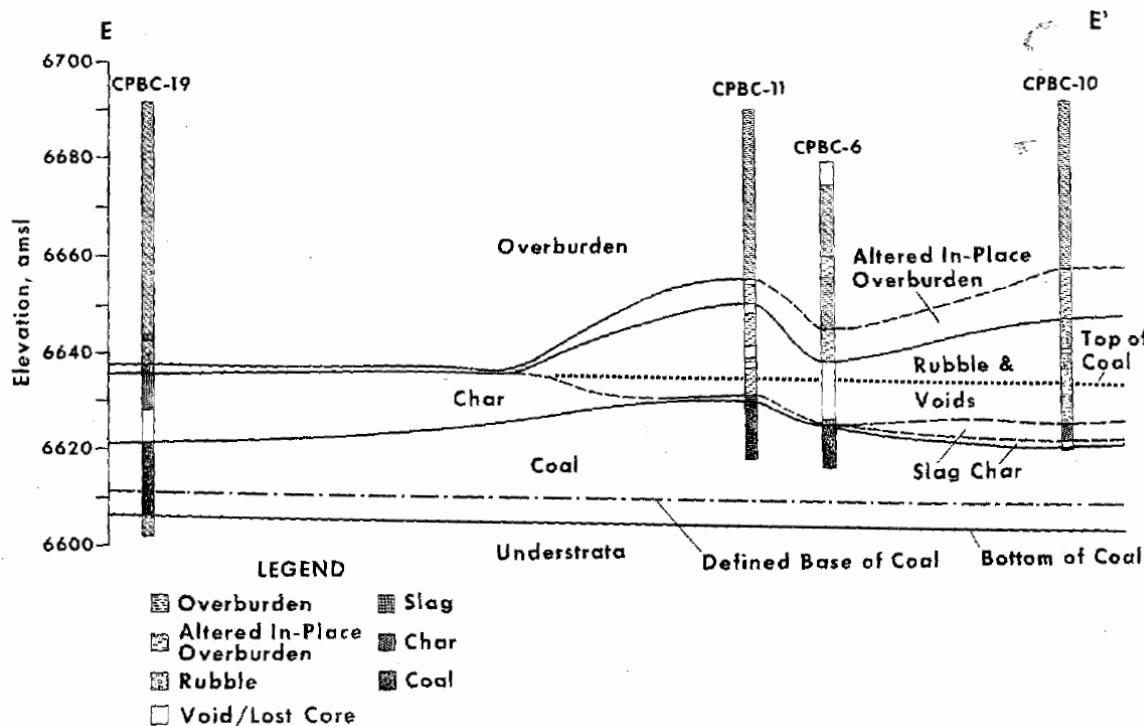
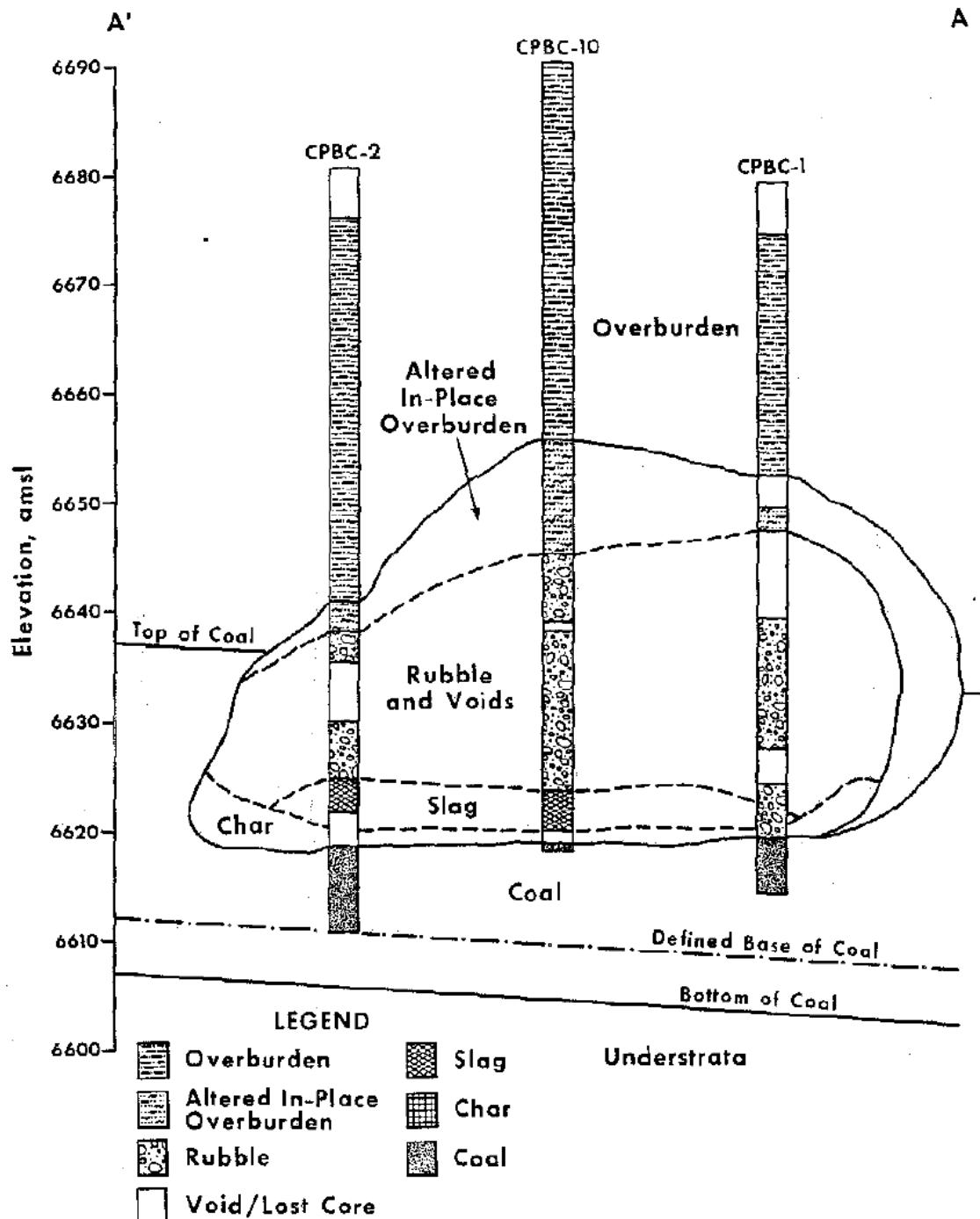


Figure 26. Rocky Mountain 1's CRIP module final cavity geometry looking north, cross-section E-E'. Figure 22 shows the corresponding plan view with a scale. (Oliver et al., 1991)



**Figure 27. Rocky Mountain 1's CRIP module final cavity geometry looking west, cross-section A'-A. (Oliver et al., 1991)**

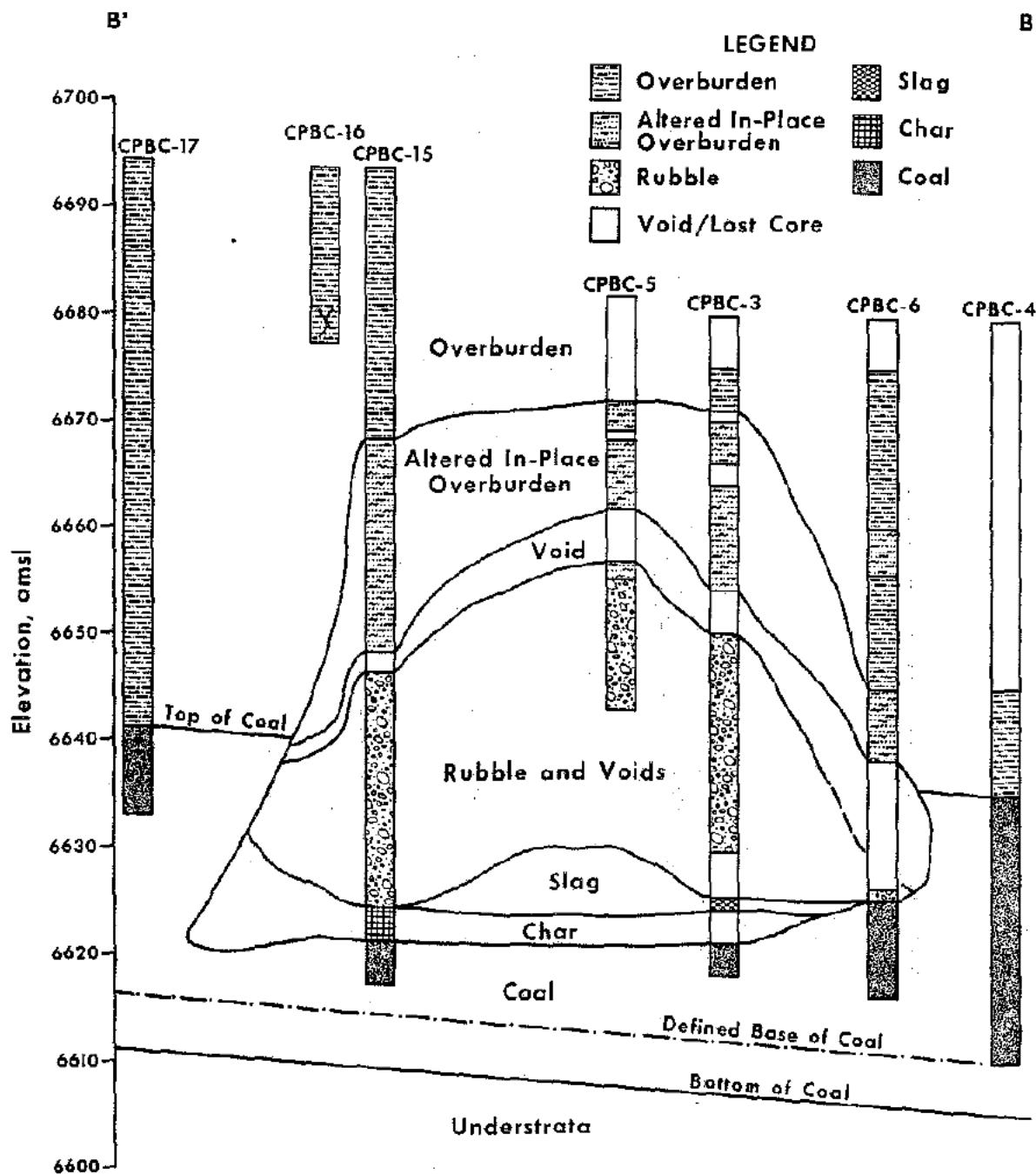


Figure 28. Rocky Mountain 1's CRIP module final cavity geometry looking west, cross-section B'-B. (Oliver et al., 1991)

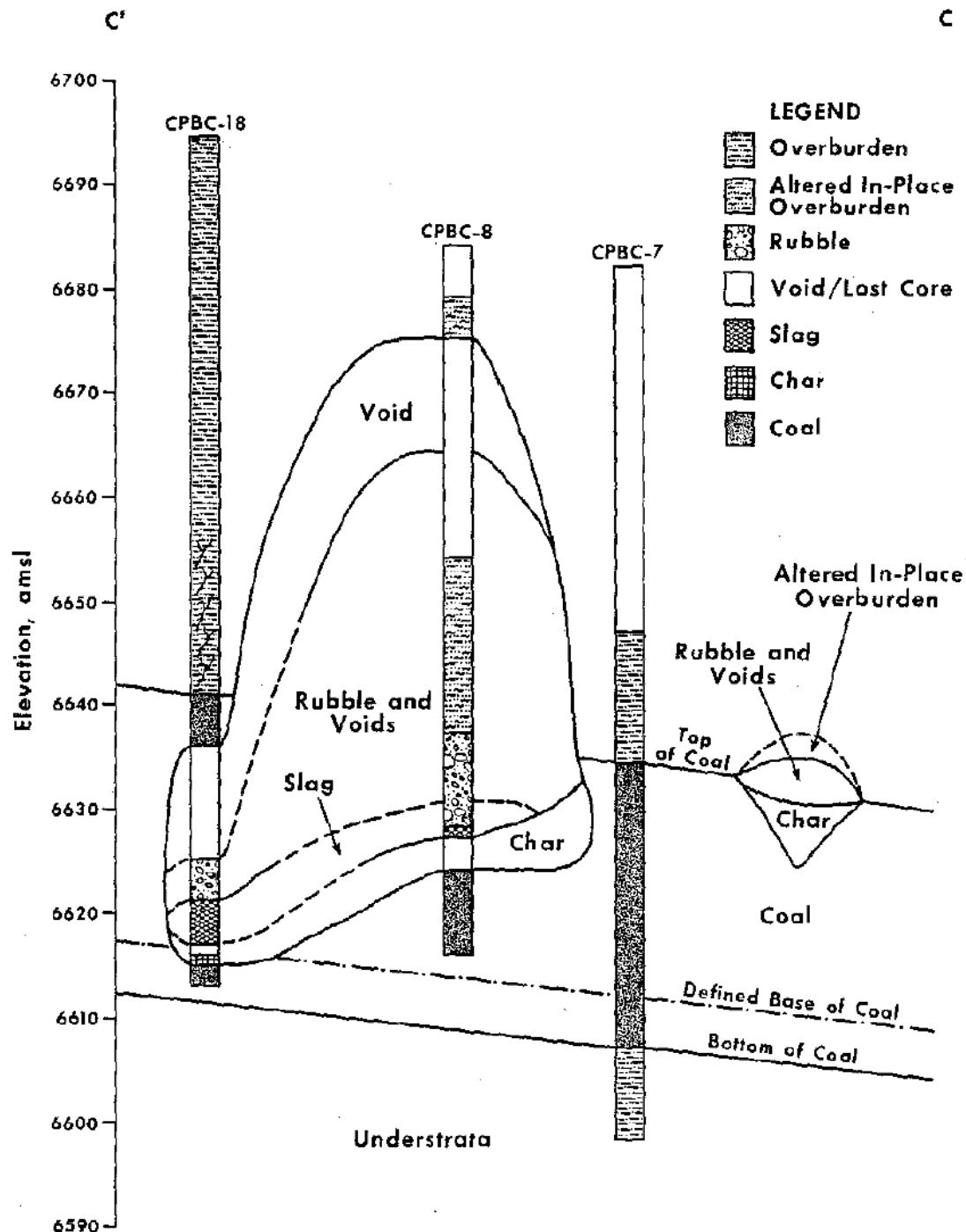


Figure 29. Rocky Mountain 1's CRIP module final cavity geometry looking west, cross-section C'-C. (Oliver et al., 1991)

#### 4.8.4.3 Performance data

Table 2 shows summary performance data for the CRIP module and the ELW module. Table 3 shows the energy balance for the steam-oxygen periods of the first CRIP cavity and the entire ELW module.

**Table 2. Summary data for the CRIP module, the individual CRIP cavities (the initial one plus the three that followed each CRIP maneuver), and the ELW module. The first two rows (days and Mg) include the air injection forward-burn stabilization phases of the ELW and the 1st CRIP cavity. All other rows of intensive properties are for oxygen-steam periods only. (Cena et al., 1988a,b)**

Module	CRIP	CRIP 1 <sup>st</sup>	CRIP 2 <sup>nd</sup>	CRIP 3 <sup>rd</sup>	CRIP 4 <sup>th</sup>	ELW
<b>Duration (days)</b>	93.0	43.8	19.9	20.0	9.3	57.4
<b>Coal Gasified (Mg)</b>	10,184	3,719	2,159	2,277	798	4,030
<b>Gas HHV (MJ/Nm<sup>3</sup>)</b>	11.3	11.7	10.8	11.6	9.7	10.3
<b>H<sub>2</sub> (dry mol %)</b>	38.0	38.0	38.0	39.0	40.0	31.0
<b>CH<sub>4</sub> (dry mol%)</b>	9.4	10.5	8.6	9.5	6.7	10.1
<b>CO (dry mol%)</b>	11.9	11.6	10.8	14.3	9.9	9.0
<b>CO<sub>2</sub> (dry mol%)</b>	38.0	37.0	40.0	35.0	42.0	44.0
<b>O<sub>2</sub>/C (mol/mol)</b>	0.27					0.35

**Table 3. Computed energy distribution as a percent of the consumed coal heat of combustion for the ELW module and the first CRIP cavity during their steam-oxygen period. The basis is the heat of combustion of the coal that was pyrolyzed, gasified, and/or combusted. (Thorsness and Britten, 1989a)**

	CRIP	ELW
Heating value of combustible gas product	62.4	52.1
Heating value of combustible tar product	6.1	5.9
Sensible heat of gas product	2.7	3.2
Sensible and vaporization heat of in-situ water influx converted to product steam (~30% from rock drying; ~70% from permeation inflow)	0.7	3.4
Sensible and vaporization heat of added cooling water converted to product steam	0.0	0.6
Heating value of char left underground	20.1	21.6
Sensible heat of char & ash left underground	0.6	0.7
Sensible heat of overburden rock left underground	7.0	12.3

Figure 30 shows how a common efficiency parameter, product heating value divided by injected oxygen rate, varies with time through the test. Steam-oxygen operation started on day 12 in a young cavity with the initial injection point. The efficiency was high, but steadily declined over time as had

been observed in nearly all other field tests including the ELW, as the ratio of roof material being dried and heated increases. A CRIP maneuver on day 53 moved the injection point back 18 meters from its first location into new coal, low in the seam (see Figure 23 above). After establishing itself the efficiency recovers to close to its previous value, then declines again, apparently because of roof heat loss. Subsequent CRIP maneuvers renewed the efficiency. By the fourth maneuver, the gain is short-lived and efficiency is down somewhat. This was not fully understood, but possibly related to water permeation, with increase in ratio of cavity perimeter to coal burning.

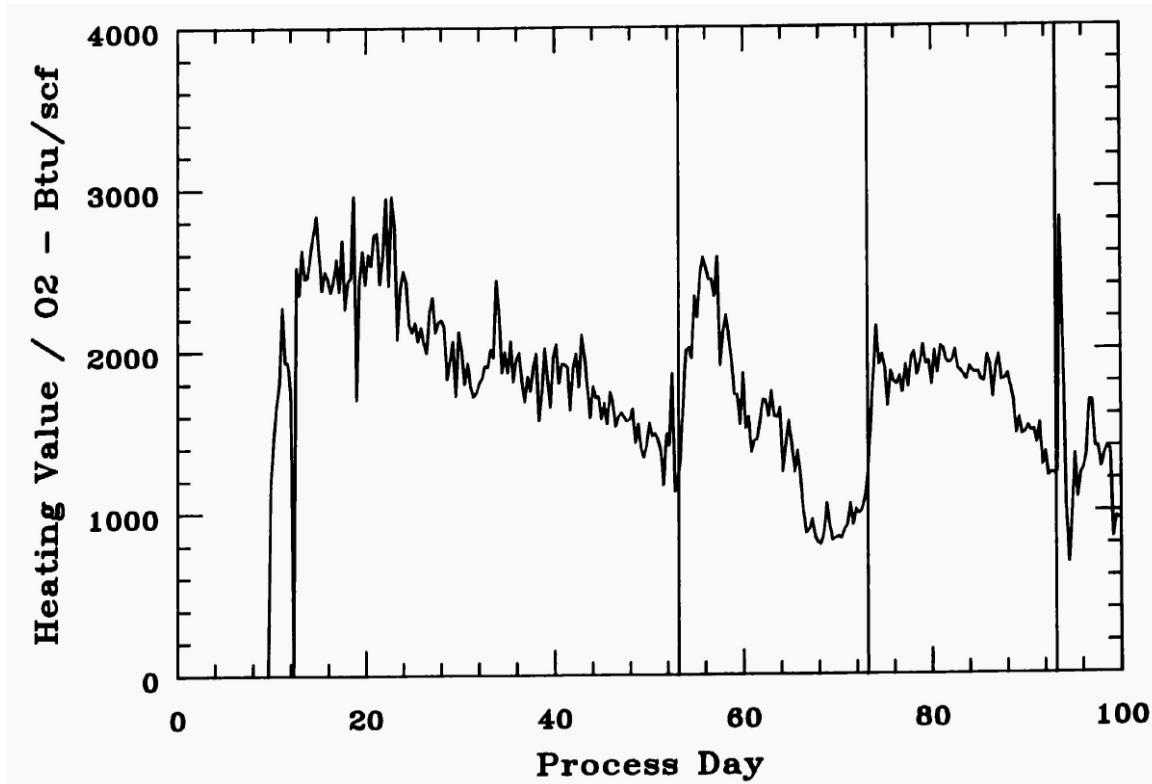


Figure 30. Process efficiency parameter (product heating value divided by injected oxygen rate) as a function of process day for the RM1 CRIP module. Vertical lines show the times of CRIP maneuvers. (Cena et al., 1988b)

#### 4.8.4.4 Observations and conclusions

The CRIP module, using an oxygen-steam mixture for injection, produced high quality gas with efficiency metrics equal to those of surface gasifiers (Thorsness and Britten, 1989c).

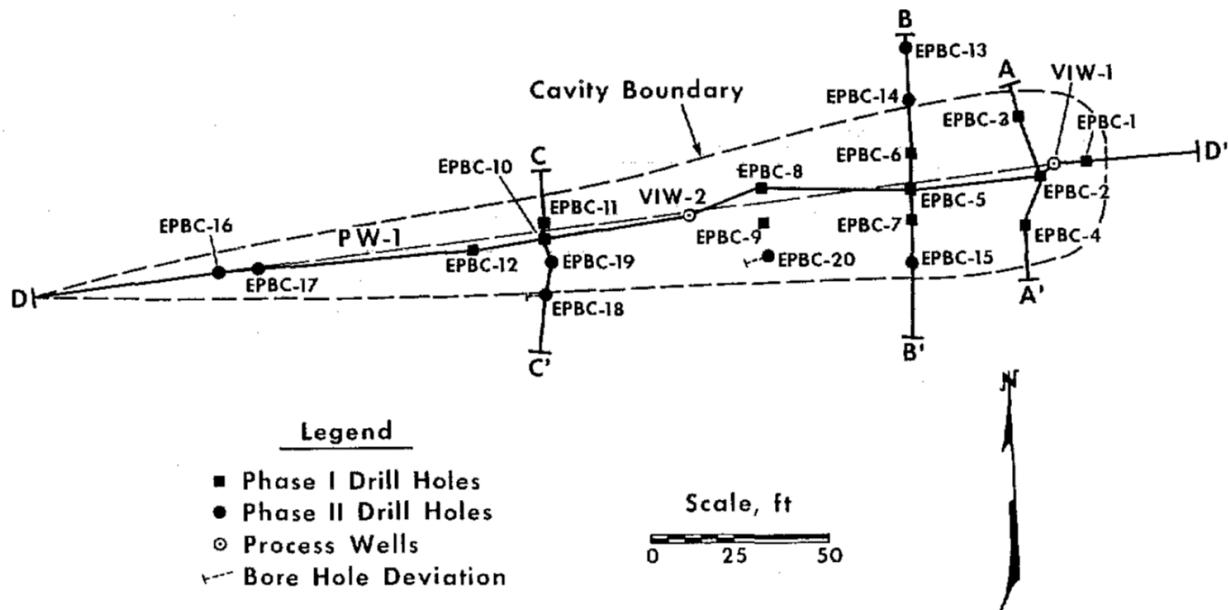
CRIP was demonstrated at a greater scale and with several more maneuvers than in the Centralia test. CRIP appeared to happen sometimes by itself by extreme cavity heat burning through the liner. While unintended, these gradual recessions may be desirable for performance. Further development may find an optimum for “auto” CRIP movements and technical ways to achieve them.

The CRIP module showed that for a given injection point, the performance started high, but declined with time as heat losses to roof rock rubble increased. But each time that CRIP was used to move the injection point back into new coal and start a new burn there, the gasification performance rejuvenated back to high performance. Increases of as much as a factor of two in product gas quality were seen after initiation of a new cavity.

## 4.8.5 ELW Module

### 4.8.5.1 Wells, links, and summary of operations

Figure 20 above provides a general schematic of the ELW module. Figure 31 is a plan view of the ELW module, including the horizontal production borehole (long dash), the vertical injection wells VI-1 and VI-2 (VIW-1&2 in the figure), the resulting cavity boundary, and locations of related cross-sectional views. The casing endpoints of the two vertical injection wells were in the top 2 meters of the coal seam instead of the bottom as planned. The horizontal borehole was thought to be in the bottom half of the seam; it was cased from the surface to about 90 meters from VI-1.



**Figure 31. Rocky Mountain 1's ELW module plan view, including the horizontal production borehole (long dash) which is cased to the left (west) of the "D", vertical injection well VIW-1, and final cavity boundary (dash). (Oliver et al., 1991)**

Ignition in each of the vertical injection wells was accomplished by injecting pyrophoric silane followed by a methane/air mixture and took a few attempts and some modifications. Directional drilling technology at the time was such that the wells missed each other by about 2 meters. Reverse burns were used to make the short connections. The reverse-burn connections took a few days and used air injection pressures up to 14 bar gage, 4-7 bar above hydrostatic. They were preceded by air acceptance testing that used air injection pressures up to 15 bar gage.

A seven-day period of "stabilization" followed, when air was injected into VI-1 and slowly increased to 1000 scfm, allowing development of the ELW cavity. Production was out of the P-1 well. Injection pressure (which is only slightly higher than cavity pressure) during this time was about 7 bar gage. Injection switched to an oxygen-steam mixture, the system stabilized, and baseline conditions set to 500 scfm oxygen, 1000 scfm steam, and 6.8 bar gage pressure.

Gasification continued with oxygen-steam injection for another 35 days during which injection composition and rates were varied experimentally over limited ranges. The ELW module operated for 46 days, including the air stabilization phase. Pressures during this period were slowly decreased to

stay below surrounding hydrostatic pressures, guided by monitoring of the growing cone of depression around the module. Four days before the end of this period, gas quality declined from 11.4 to 9.2 MJ/Nm<sup>3</sup>, suggesting this cavity had reached its declining phase. In all, about 4,000 Mg of coal was gasified with an average gas heating value during the steam-oxygen period of 10.4 MJ/Nm<sup>3</sup>.

The switchover to VI-2 as the injection well was not successful despite much effort. Unacceptably high oxygen levels in the product gas began to be seen which could not be remedied and the module was shut down for safety considerations.

Injection was stopped but venting was allowed to continue through P-1, maintaining the pressure at the levels of the CRIP module so-as to not influence that continuing test. Post-burn Clean Cavern operations beginning with depressurization of both modules started after the CRIP module was done.

#### **4.8.5.2 Cavity geometry**

Figure 31 above shows the final cavity shape in plan, along with the cross-section locations. Figure 32 and Figure 33 show the lengthwise cross-section and one of the cross-sections perpendicular to the production borehole. (Oliver et al., 1991)

It has already been noted that the injection wells were only completed to the top meter or so of the coal seam. Although the horizontal product borehole was thought to have met its objective of being in the bottom half of the seam, its presence was unable to force the burn to go much lower than halfway down. From the cross-sections, it appears that the effective seam thickness (the fraction that was utilized because of the borehole and well completion locations) was about 5 meters.

The cavity width was in the vicinity of the injection well was roughly 15 meters or about 3 times the thickness of the gasified coal. The height of roof rock that fell into the cavity or was thermally altered was typically 2 to 3 times the height of the coal below it that was converted.

#### **4.8.5.3 Performance data**

Performance data for the ELW module was given in the CRIP section (4.8.4.3).

#### **4.8.5.4 Observations and conclusions**

The incorrectly placed injection well completions of the ELW module handicapped it, making a side-by-side comparison of performance between it and CRIP unfair. Thorsness and Britten (1989c), commented that “The vertical injection well geometry used in the ELW [module] suffered from the handicap of not providing an assured bottom seam injection point. Thermal data, process data analysis and post burn coring all indicate that the ELW module burned primarily near the top of the seam involving a proportionately large amount of overburden.” Having the burn near the top of the seam resulted in poor thermal efficiency and gas quality because of the relative magnitude of heat loss to roof rock rubble drying and heating to coal energy.

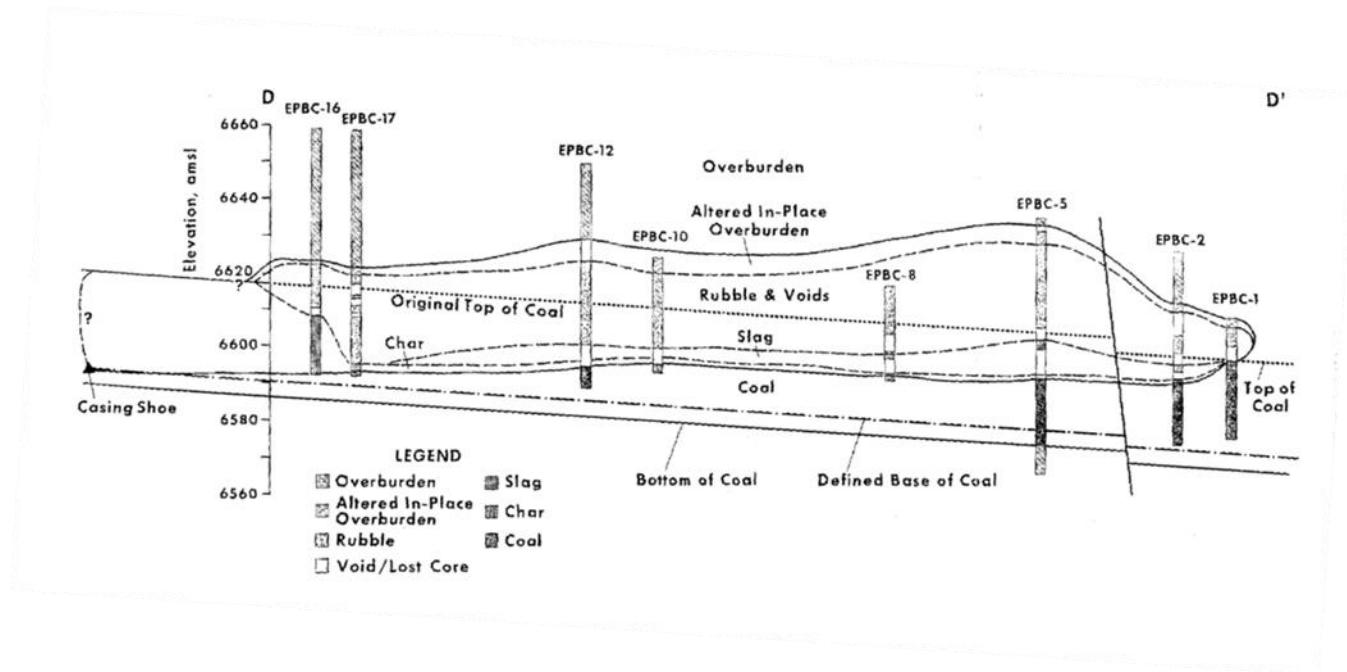
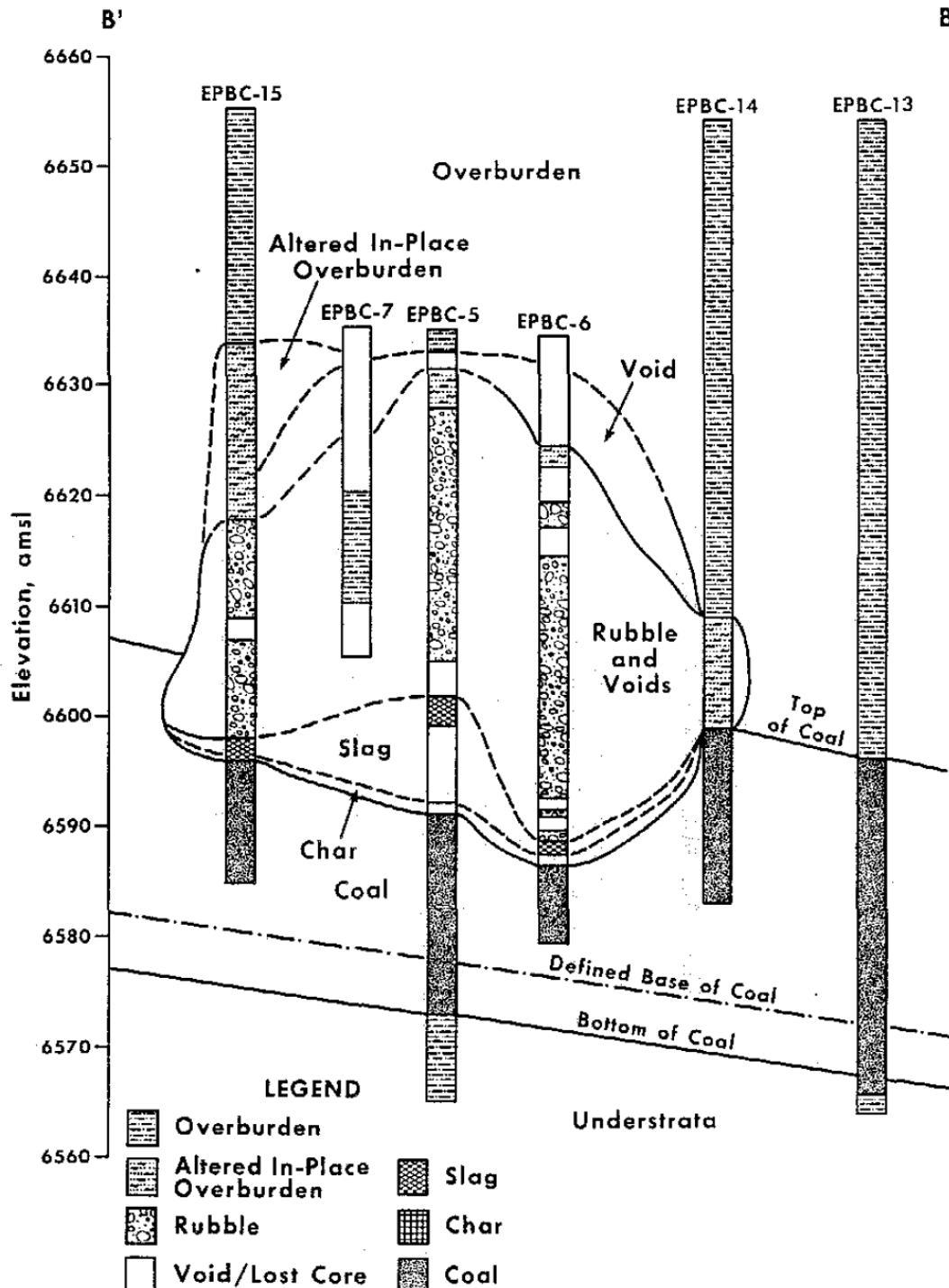


Figure 32. Rocky Mountain 1's ELW module final cavity geometry looking north, cross-section D-D'. The injection well was close to EPBC-2 in the top meter or so of the coal. The production well borehole was uncased to the right (east) of the "Casing Shoe" callout. (Oliver et al., 1991)



**Figure 33. Rocky Mountain 1's ELW module final cavity geometry looking down-flow (west) toward the production well, cross-section B'-B. (Oliver et al., 1991)**

#### 4.8.6 General operation and performance observations for Rocky Mountain 1

The RM1 test demonstrated: the importance of a bottom-seam injection point; the feasibility of the CRIP process and multiple maneuvers at field-test scale, and that UCG can produce a gas quality with efficiency metrics that are comparable to surface gasification processes. (Thorsness and Britten, 1989c). The CRIP module averaged about 11.3 MJ/Nm<sup>3</sup> and the ELW module 10.3 MJ/Nm<sup>3</sup>. However, by other metrics tied to efficiency, the CRIP-ELW difference was much more dramatic. For example, the ratio of product heating value to injected oxygen was 50% higher for the CRIP module than the ELW module. The CRIP module's superior performance is directly traceable to differences in geometry. The CRIP method assured that the injection point was always low in the seam, and CRIP maneuvers were able to generate new cavities whenever the cavity grew big enough to involve much overburden. The ELW module suffered from a high injection point, making the burn primarily near the top of the seam, thus involving a proportionally large amount of overburden.

The ELW and CRIP modules clearly showed by contrast the benefit of having the injection point at the bottom of the seam and the detriment of having it near the top of the seam. From Thorsness and Britten (1989a), for both ELW and CRIP modules, about 30% of the computed water influx came from drying of roof rock, 70% from permeation inflow. But heat loss to rock sensible heat outweighed water influx in the energy balance magnitude. “increased interaction with the overburden, and not increase flowing water influx, was the primary reason for the poorer performance of the ELW module compared to the CRIP module.”

The extent of upward roof heating and rubblization was less in the CRIP module than the ELW module, despite having a slightly larger effective coal seam thickness, slightly wider cavity, and much greater duration of operation and quantity of coal processed. This is probably because the CRIP process frequently moved the injection point, reducing the duration of time that any one roof area is exposed to the hottest conditions.

The different elevations, and hence the different surrounding groundwater pressures and target operating pressures, of the two modules proved to be an operating challenge. While manageable in theory it requires a bit more sophistication in engineering design and control.

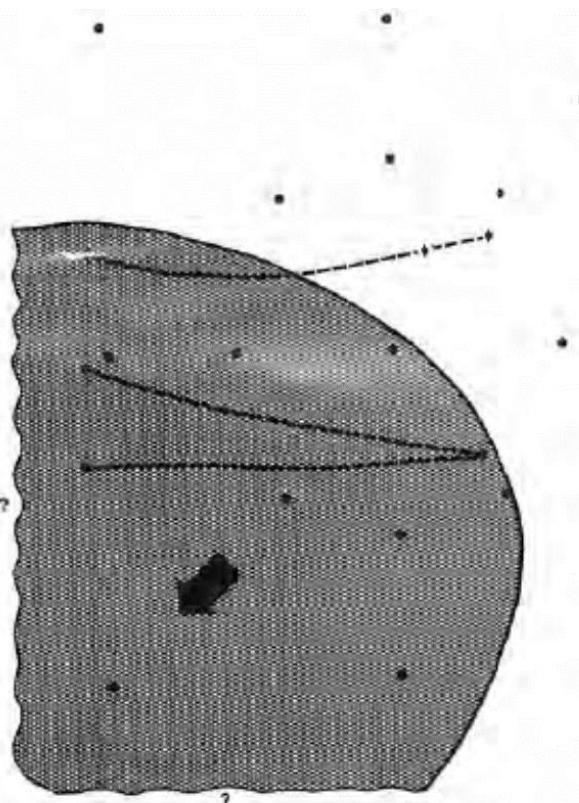
There was more hydrological connectivity and fluid/pressure interaction between the two modules than had been anticipated based on pre-burn characterization. For example, ELW was in forward gasification mode (air stabilization phase) when the high-pressure reverse-burn connections were being made in the CRIP module, and these resulted in oxygen levels up to 1% in the ELW product stream at that time (Cena et al., 1988a).

#### 4.8.7 Reverse-burn overpressure drove contaminant-laden gas out briefly

Drilling technology of the time resulted in boreholes missing their intended intersections by a few meters. Reverse burns were used to make these short connections in both the ELW and CRIP modules. Speaking of the CRIP module, but applicable to both modules, Cena et al. (1988a) said “the linking phase of the test was of short duration, but was by far the most taxing phase in terms of the physical plant and personnel. Also, high pressures used for air acceptance tests and linking phases may have produced local, unwanted increases in permeability ... Startup and subsequent operation would have been much easier had mechanical connection of the wells existed ...”

In addition to the inconvenience, the high air pressures (4-7 bar over hydrostatic) used to reverse-burn the short connections between missed intersections drove product gas outward more than 200 meters, mainly in the southwest direction as shown in Figure 34. (Beaver et al., 1988) Contaminants were found up-dip in excess of permit requirements and WDEQ could have terminated test operations. In 1988 hindsight this

was predictable, but it was unanticipated at the time the operations were done. Fortunately, the behavior of the nearby monitoring wells led to this being discovered promptly so that mitigating actions could be undertaken promptly. The team figured out and explained the cause, took interim actions to reduce the pressure and bring water back into the volume where gas had escaped, and convinced regulators that future operations would follow the pressure-below-surroundings rule. The field test was allowed to proceed. (Dennis, 2006).



**Figure 34. High injection gas pressures that occurred during the brief reverse-burn connection-making operations at RM1 drove gas including pyrolysis and gasification products out and up-dip more than 200 meters. (Beaver et al., 1988)**

The high pressures used during air acceptance testing that preceded reverse burn operations caused some of the monitoring wellhead flanges to mechanically fail. The pressure pathway for this is from the injection well into and through the formation to the open/screened bottom of the monitoring well, and up the monitoring well.

These same high pressures were thought to create flow/pressure pathways between the two modules with gas permeability much greater than expected from pre-test site characterization and pump tests.

Drilling navigation has improved greatly since 1987. Now intersections are likely to be very precise, requiring less effort, pressure, hassle, and time to connect them.

#### 4.8.8 Clean Cavern Concept for minimizing groundwater contamination

Previous experiences at Hanna, Hoe Creek, Rawlins, the lignite experiments in Texas, and others had sensitized the program to the challenge and importance of minimizing groundwater contamination. Managing and characterizing this was a major objective of the RM1 test. The site was characterized before the test and the Wyoming Department of Environmental Quality (WDEQ) permitted and payed attention to the operation. Numerous groundwater monitoring (piezometers) and sampling wells were installed close to and surrounding both modules.

The Clean Cavern Concept is described in Section 8.1. It was adopted and used during and after RM1 operations (Covell et al., 1988 and Boysen, et al., 1990). Except for the high pressures needed to accomplish the reverse-burned connections between nonintersecting wells, the operators did a good job at monitoring the piezometric heads around both modules and continuously adjusting cavity operating pressures downward to accommodate the expanding and deepening “cone of depression.” In all, the Clean Cavern operation and post-burn procedures were successful in minimizing the inventory of contaminants left underground, minimizing their outward transport during operations, maximizing their removal from the underground immediately after operations, and containing them in the years after. The venting and steam-flushing activities at RM1 produced a large quantity of contaminants that otherwise would have stayed in the underground system. As a result, the magnitude and spatial extent of groundwater contamination at RM1 was fairly small.

The following passages quote from the abstract in Boysen et al. (1990): “Upon completion of the RM1 UCG field test, simple low-cost procedures were initiated to reduce groundwater contamination from the test. ... Steam was injected into and produced from each of the two RM1 UCG cavities were continuously vented to remove effluents and to enhance groundwater influx. The groundwater influx provided additional cooling of the cavities, thereby minimizing postburn pyrolysis. Groundwater influx also stripped contaminants from the surrounding coal, char wall, and cavity and prevented further transport of contaminants away from the UCG cavities. Thus, many of the contaminants generated during gasification and most of the contaminants generated after gasification were transported to the surface, minimizing UCG’s impact on local groundwater.”

### 4.9 Other field tests

#### 4.9.1 Gorgas (USBM)

Initial UCG activities in the U.S. were carried out by the U.S. Bureau of Mines in 1947-1960 near Gorgas, Alabama. The program included multiple field tests, used or explored combustion in mine tunnels, grouted boreholes, hydraulic fracturing and electro-linking to prepare the seam, and tried oxygen-enriched air. The small amount of data available conveniently from secondary sources appears in Table 1 above. There are very few references to these tests in the U.S. literature of the 1970’s and it appears that the Gorgas program did not play a significant role in informing that later generation of U.S. UCG researchers. Original references include a UCG review of that era, Elder (1963), a series of U.S. Bureau of Mines technical reports, including Dowd et al. (1947), Elder et al. (1951), Elder et al. (1957), Capp et al. (1960), and Capp and Plants (1962), and a bibliography of that era, Capp et al. (1963).

#### 4.9.2 Tennessee Colony and Fairfield lignite tests (Basic Resources)

Basic Resources, a subsidiary of Texas Utilities, purchased the U.S. rights of the Soviet UCG technology in 1975. They operated a 26-day air-blown test in 1976 near Fairfield, Texas, producing 4.7 MJ/Nm<sup>3</sup> gas. (Edgar, 1983 and Stephens et al., 1985). This may also be called the Big Brown test.

In 1978-1979 they operated a test near Tennessee Colony in Anderson County, Texas, on a 2.2-meter seam. The air-blown phase of this lasted 197 days, consumed roughly 4100 Mg of coal, and produced gas averaging only 3 MJ/Nm<sup>3</sup>, with high CO<sub>2</sub> concentrations. The oxygen-blown phase lasted 10 days, consumed about 190 Mg of coal and produced gas averaging 8.6 MJ/Nm<sup>3</sup>. Efficiency suffered from heat losses to the over-burden and water influx from adjacent sand formations.

#### 4.9.3 Alcoa and Byron lignite trials (Texas A&M Consortium)

A corporate consortium led by Texas A&M University carried out three short and small tests in Texas lignite, all air-blown (Edgar, 1983; Stephens et al., 1985; and GasTech, 2007). Operations and results were poor. In 1977, in Bryan, Texas near College Station (at a site that may have been called Easterwood), a 1-day trial on a 0.6-1.2-meter-thick seam produced gas with a heating value between 1.3 and 4.2 MJ/Nm<sup>3</sup>. Problems included sand control, excessive water production, heat loss due to the thin seam, casing problems, and air/gas bypass. In 1979, at a site near Alcoa, Texas (referred to, probably incorrectly, in one reference as Bastrop County) a 2-day trial on a 4.5-meter seam produced gas with a heating value of 3.2 MJ/Nm<sup>3</sup>. In 1980, a 21-day trial at this same Alcoa site produced gas with a heating value between 1.3 and 5.6 MJ/Nm<sup>3</sup>. Problems with this included mechanical failure of well casings due to thermal expansion, and it can be inferred that they failed to achieve reverse-burn linkage even after adding wells to reduce the spacing to 9 meters. (Edgar, 83-SoA; Stephens, 1985; and GasTech, 2007)

#### 4.9.4 Carbon County (Williams)

“In 1995, Williams Energy conducted a UCG pilot project in Carbon County near Rawlins, WY. This test was located adjacent to the Rawlins UCG trials that were conducted by Gulf R&D Company in the late 1970’s. The test was conducted in the same [steeply dipping] coal seam as the Rawlins tests; however, it was performed at deeper levels. ... The test was unsuccessful and resulted in groundwater contamination due to poor well linkage and operation of the UCG reactor above hydrostatic pressures.” (GasTech, 2007). The site was in the Indian Springs Coal Resource area and the tests were conducted in April and August of 1995. Organic compounds including benzene increased in concentration after the burn in groundwater within the coal seam and in overlying and underlying sandstone units.

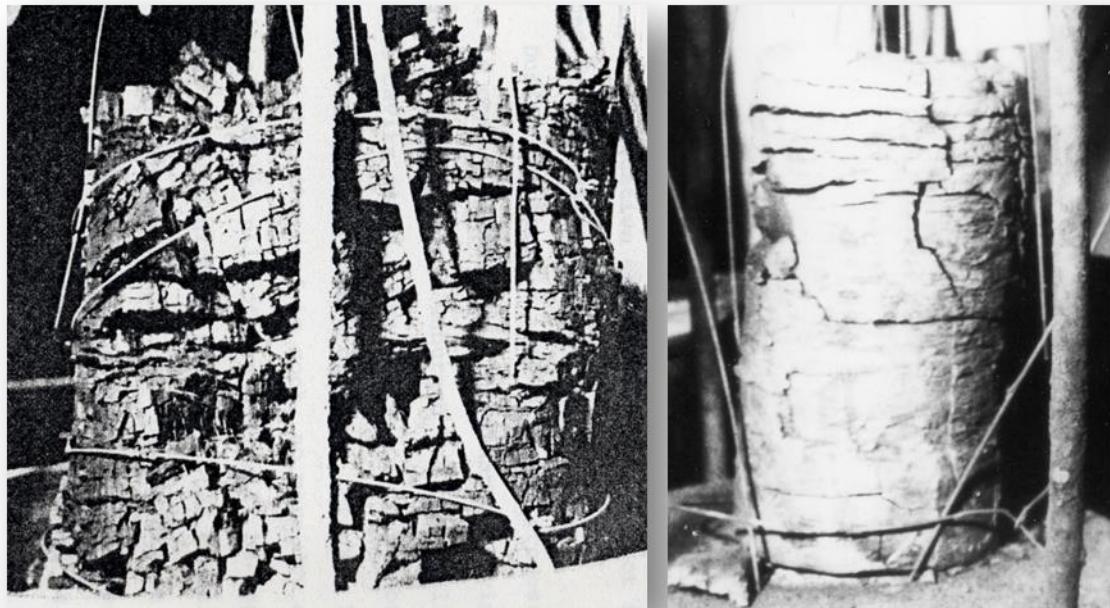
### 5 Laboratory experiments

Laboratory experiments did not comprise a large share of the U.S. UCG program of the 1970’s and 1980’s. The keys to taking UCG from concept to industry were correctly perceived to be operations (choice of “methods,” design and construction details, hardware such as well-completions, operating decisions, etc.) and the complex interactions between the process and its underground environment. Coal pyrolysis and gasification chemistry were already reasonably well known from research motivated by surface gasification and pyrolysis. The chemistry sub-models for UCG could make use of reaction sets, equilibria, and kinetics available from that literature. Transport phenomena were understood well in general, with the crux of modeling them for UCG being the specific local environments in a real UCG system. It is difficult to duplicate in the laboratory so much of the phenomena that is important to UCG at a relevant scale and system complexity.

Some technology and equipment tests and specific operational questions often used lab experiments. For example, lab tests by LLNL had shown that a reverse burn would not proceed upstream with air flowing through a bored hole in the coal. So, when that was observed in the preparation phases of Hoe Creek III, they were ready with alternatives – enriching the air with propane (below the lower explosion limit) or oxygen, and the latter worked in the field. Ignition and CRIP tools and operations were also tested in the lab.

Some laboratory experiments informed the qualitative understanding of phenomena. For example, seeing photographs of overburden and coal cores that had been heated to high temperatures (Figure 35, Westmoreland and Dickerson, 1979) helped this author conceive and formulate the concept of spalling-enhanced drying that provides one of the explanations for rapid upward and side-wall growth of the cavity and its filling with a bed of coal and rock rubble. (Camp et al., 1980).

WRI's experiments on groundwater contamination transport and adsorption helped inform their development of the Clean Cavern Concept discussed later.



**Figure 35. Cores of lignite (left, 15-cm diameter) and Hoe Creek overburden (right, 5-cm diameter) broke apart at centimeter-scale spacing upon heating. (Westmoreland and Dickerson, 1979 and Hightower, 1980)**

## 6 Modeling

### 6.1 Introduction

Much effort in the U.S. has been devoted to mathematical modeling of UCG during both the main and the recent eras. Some are high-fidelity, multi-physics, integrated models of the full UCG process and its most important phenomena. Some are very simplified engineering models of the full process that may be used for estimations. Others are multiphysics models of one phase of the process, and others are high fidelity models of single aspects of the physics or chemistry. This is not a full review, but a brief description of a few of the best or most useful models that fall into the first two of these categories.

### 6.2 High-fidelity, multi-physics, models of the UCG process and cavity growth

Good models of the UCG process must be based on an accurate conceptual model of the UCG process that is consistent with observations of the cavity and the nature of its growth (Section 7.6). Many of the earlier modeling efforts were not adequately informed by field test observations. Models based on either permeation of reaction fronts within porous coal, or open cavity gas flow with conventional heat- and mass-transfer to a reacting coal wall do not accurately depict the realities that were observed in U.S. field tests.

The model of the 1970's and 1980's that most accurately and completely captured the important aspects and phenomena of UCG was LLNL's CAVSIM model (Britten and Thorsness, 1989; Britten and Thorsness, 1988; and Thorsness and Britten, 1989b). The strength of this model is that it was based on the observations and understanding that field test experience, data, and analyses provided. It accurately depicted the key features that had been observed during UCG operations, drill-backs, and, very importantly, personal inspections of excavated UCG cavities at early, mid, and late stages of growth. As illustrated in Figure 36-top, CAVSIM modeled a single cavity in a horizontal seam that was constrained to be 2-D axi-symmetric (i.e. varying only in vertical and radial directions), with a fixed injection point on the axis low in the coal seam. It included the essential chemistry, heat transfer, gas transport, water permeation influx with both a saturated and unsaturated zone in the surroundings, upward and outward cavity growth by spalling of coal and overburden, accumulation of coal, char, ash, and roof rock rubble in the lower fraction of the cavity, pyrolysis, gasification, and combustion of coal at the wall and in the packed bed of rubble. It also had an added module to represent the heat transfer and chemistry in the downstream link between the main rubble-filled actively burning/gasifying cavity and the entrance to the production well. It accurately reproduced both the approximate cavity shape, water influx, and product gas compositions for the Centralia PSC test and the first two cavities of the RM1-CRIP module (Figure 36-middle and bottom).

More recently, a different LLNL team developed a modern high-fidelity multi-physics integrated model of UCG called UCG-SIM3D (Nitao et al, 2011; Camp et al, 2013). It models essentially the same phenomena as CAVSIM, but takes advantage of modern computational capabilities, algorithms, and software elements of other codes. Important advances over CAVSIM include: flexible 3-D geometry, including multiple seams, and rock strata, dip, and spatially-varying properties of the geological materials; flexibility to move one or more injection points and production points to locations that can change with time; a sophisticate algorithm that tracks 3-D growth of the cavity and rubble boundaries and rubble composition; an improved 3-D model of flow, reactions, and heat transfer within the rubble bed and in the open void region; a 3-D non-isothermal unsaturated water and gas flow model for the surroundings. As with CAVSIM, sideward and upward growth of the cavity in coal and overburden rock

is by spalling, with user-specified rate coefficients in a temperature-dependent model. The code structure would allow for interface with a geomechanics code that could predict cavity growth by structural roof collapse, but this was not implemented. After fitting some parameters, UCG-SIM3D very accurately calculated the 3-dimensional development of the cavity and its rubble contents, the 3-dimensional temperature, pressure, and composition fields, and product gas composition of the Hoe Creek 3 and Rocky Mountain 1-CRIP field tests (Figure 37, Figure 38, and Figure 39). Inputs included the complicated spatial and temporal histories of injection locations, rates, and compositions. UCG-SIM3D development ended before being matured into an engineering tool for use by non-experts.

The U.S. program developed detailed models of the reverse burn process. These were reviewed by Krantz and Gunn (1983b) and are not included here.

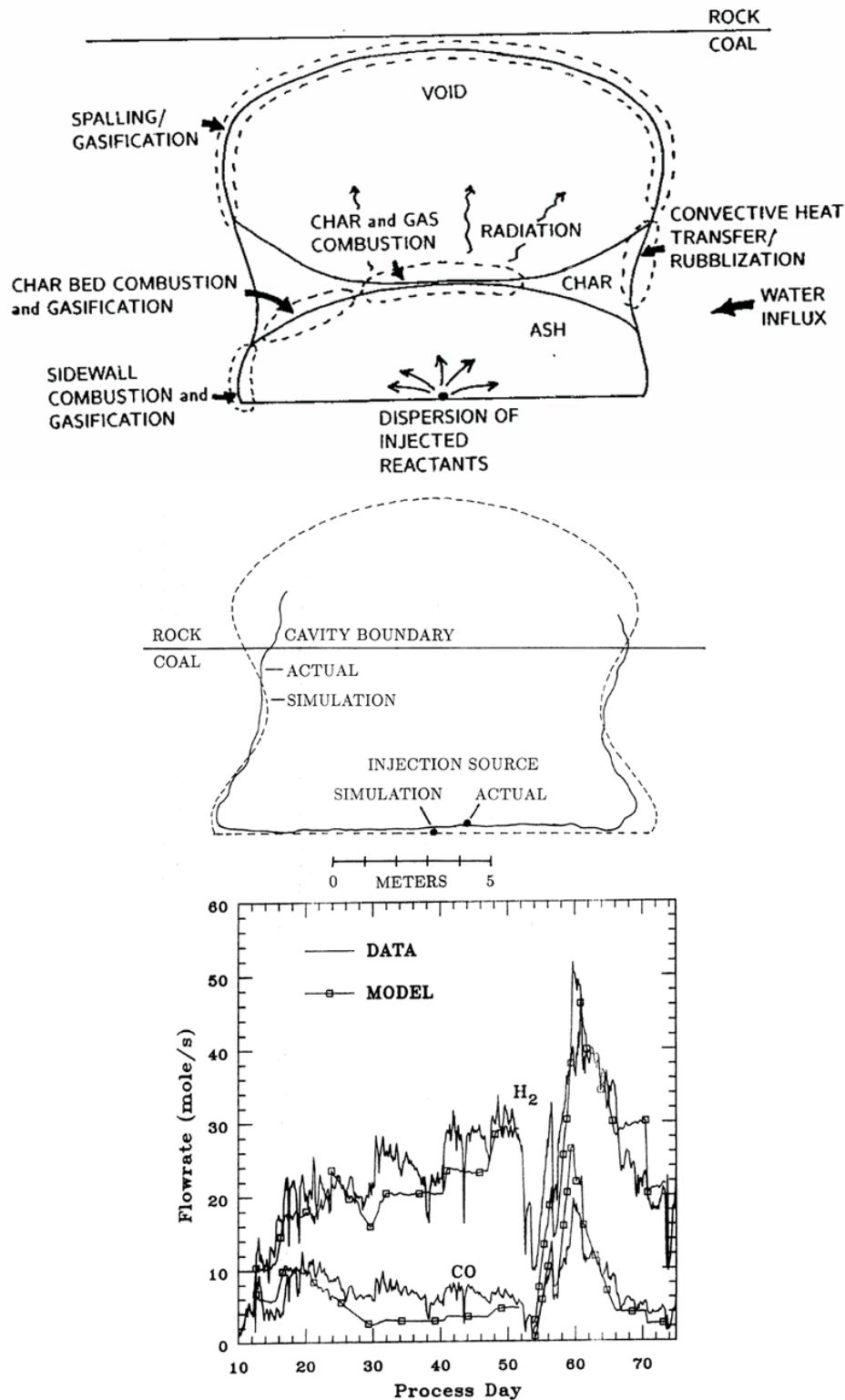
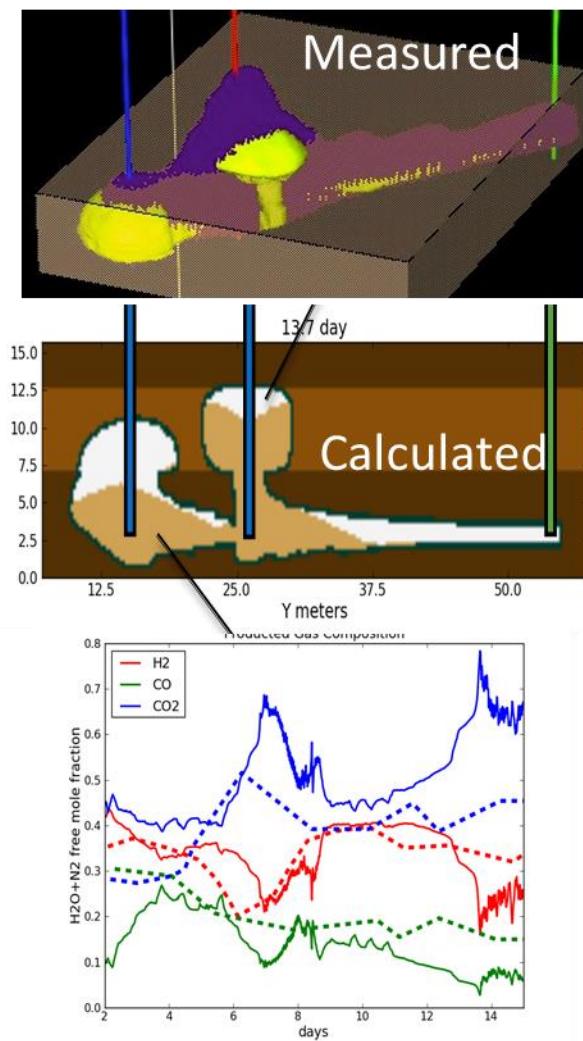


Figure 36. Top: Schematic of CAVSIM model, showing phenomena occurring in zones treated by various sub-models. Middle: Predicted and measured shape of the Centralia PSC field test. Bottom: Predicted and measured production rates of H<sub>2</sub> and CO for the first two cavities of the RM1-CRIP module. (Britten and Thorsness, 1989)



**Figure 37. UCG-SIM3D calculations of cavity and rubble geometry, and product composition, compared to measurements for the first 15 days of the Hoe Creek 3 field test. (Camp et al., 2013)**

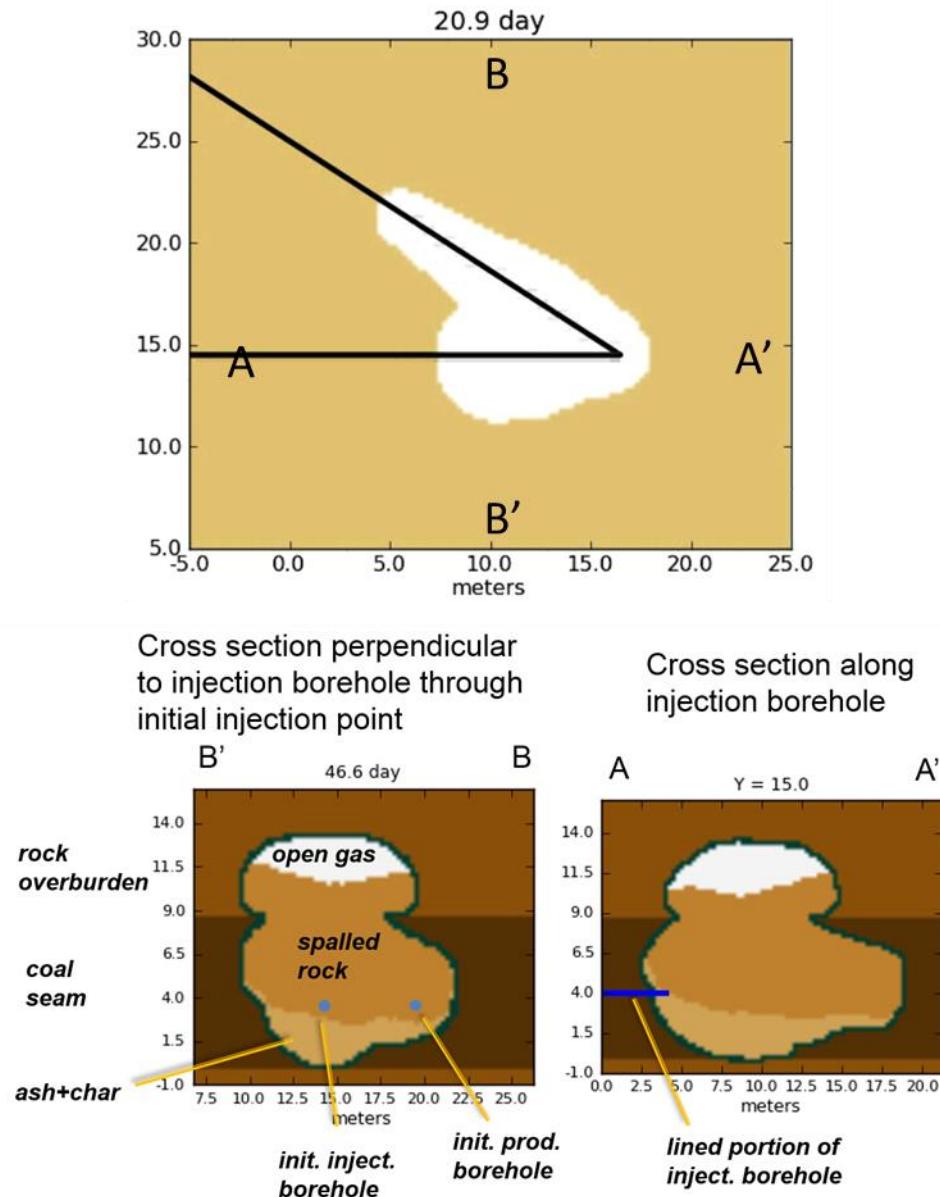
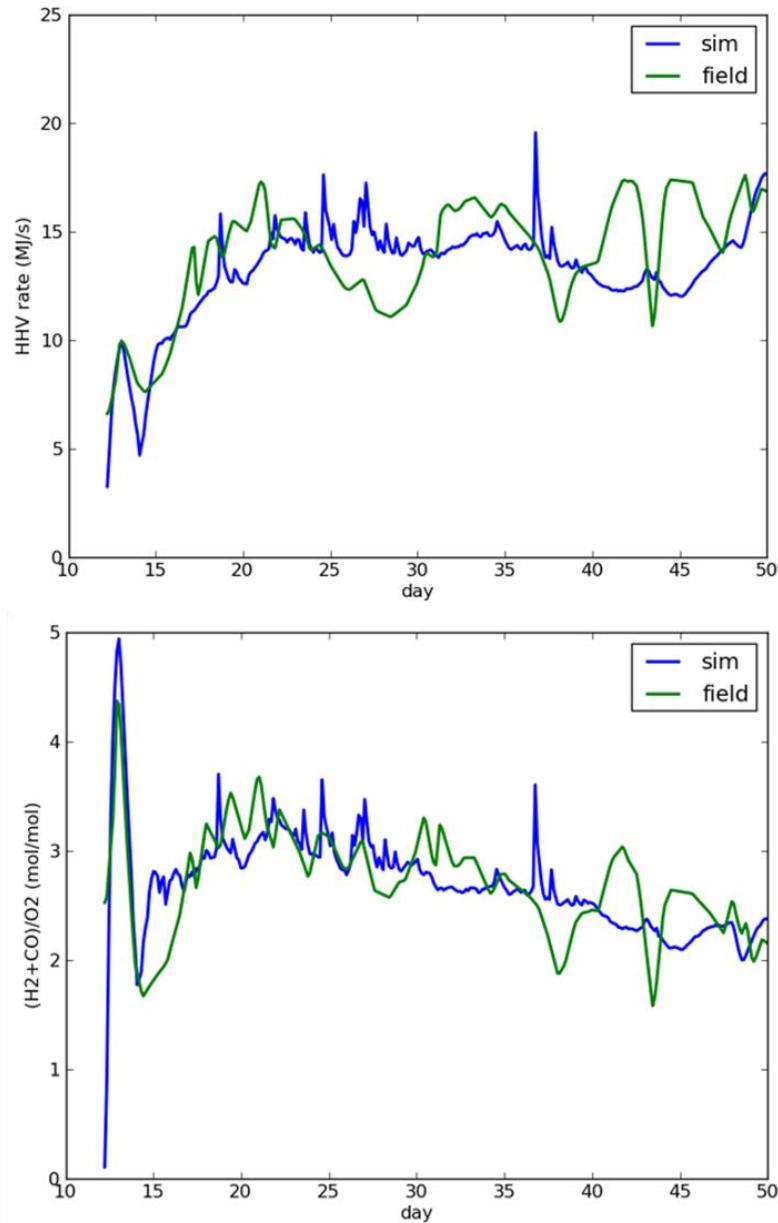


Figure 38. UCG-SIM3D calculations of cavity and rubble geometry for the Rocky Mountain 1 CRIP module. Top: plan view at 21 days; bottom: cross-sections after 47 days). (Camp et al., 2013)



**Figure 39. UCG-SIM3D calculations of product gas history compared to measurements for the Rocky Mountain 1 CRIP module. Top: heating value rate; bottom:  $(H_2+CO)/O_2$  (Camp et al., 2013)**

### 6.3 Simplified Engineering Models

Simpler engineering models were also developed in both the main and recent U.S. programs. They are generally easy to use by a competent UCG engineer and are useful for obtaining rough estimates and dependencies/sensitivities, and making trade-off studies. They require assumptions and estimates of important parameters to be provided by the user. They are typically lumped parameter models with no spatial or temporal resolution.

LLNL developed EQSC (Upadhye, 1986) to calculate energy and material balances based on a simple multi-zone model of UCG, chemical equilibrium, and a set of required inputs relating to chemical equilibrium (such as the amount of water influx and the fraction of this that enters the process before and after the water-gas shift equilibrium is set, and the methane ratio (since methane is governed more by pyrolysis than equilibrium)). EQSC was extended in recent years by LLNL to a model called UCG-MEEE (material, energy, and economics estimator) (Upadhye et al., 2013). Its core is the EQSC energy and composition model. UCG-MEEE provides side-calculations to help estimate some of the required input parameters, such as heat loss. Its calculational basis is a single module, but it envisions many UCG modules operating in parallel on industrial scale for a long project duration. Given a set of input parameter estimates and assumptions, it calculates a full material and energy balance, and estimates a selling price for the product gas to achieve a desired rate of return. The economics are based on the GasTech (2007) study and standard scaling factors. UCG-MEEE's utility for determining parameter sensitivities and trade-offs was illustrated in Burton, et al. (2012).

LLNL recently developed an engineering tool called UCG-ZEE to help screen complicated coal fields in which there are many strata of rock and coal of varying quality, with lateral variations tied to each exploration borehole and set of core samples (Shafirovich and Camp, 2012 and Reid et al., 2012). UCG-ZEE allows the engineer to explore different choices of which seams to target for UCG and at which locations. It is based on a straightforward enthalpy balance that assumes the heating value of all coal in a selected vertical interval goes to heating up to a final rock temperature all the rock within this interval, evaporating and heating up to a final gas product temperature all the water within this interval, gasifying all the coal within this interval and producing all the gas at a final gas product temperature. Typical gas composition is assumed. Rock layer moistures and dry heat capacities are by estimate or default. The engineer must choose reasonable intervals that correspond to what a UCG cavity would envelope. For example, at the Hoe Creek site, it would be unreasonable to assume you could process only the lower seam without including also the interburden, upper seam, and some distance up into its overburden in the energy balance. Outputs are the maximum theoretical (no water influx and no heat loss outside of the interval chosen) amount of product gas heating value that would be produced per areal square meter (proportional to product energy per well) and the average heating value of the coal and rock layers combined within the interval (which relates to the expected quality of product gas or the ratio of product gas heating value to injected oxygen).

## 7 Process technology, characteristics, and performance

### 7.1 Ignition

Several methods of igniting the coal downhole were used successfully. Details are in the individual test accounts. Sometimes ignition went easily on the first try. Other times it took many tries over many days with many modifications. Different experiences occurred with apparently similar or identical methods.

Some fussing was often required, experience helped, and methods and equipment evolved that made it easier. No test was cancelled because the coal could not be ignited, but sometimes failure to ignite when and where desired required changing the operation plans, with Rawlins II perhaps the worst case.

Two general types of methods were used to ignite exposed coal in a borehole, generally after pumping out free water. In the first type, which only works at the bottom of vertical wells, crushed coal and/or charcoal was placed (dropped) to cover an electric igniter, and air (sometimes enriched with oxygen and/or methane or propane, staying outside of explosion limits) is fed to the location. In the second type, a fluid that auto-ignites in air (e.g. tetraethyl borane or silane in argon) is fed to the ignition point where it contacts injected air (sometimes with oxygen and/or methane/propane enrichment) to get the initial flame, followed by flow of easy-burning hydrocarbon fuel (ranging from methane to liquid diesel fuel) and more air (or oxygen-enriched air).

Ignition proved challenging as late in the program as the final Rocky Mountain 1 field test, which took several tries and modifications in both modules to succeed. This is detailed by Thorsness, et al. (1988). They used silane-in-argon, air, methane, a special ignitor tool and special nozzles. Laboratory testing preceded and followed the RM1 fielding, and in both venues differences in behavior and success depended on relative flow directions and whether the borehole was vertical or horizontal. More research was recommended.

## 7.2 Forward gasification requires a link, not coal permeability

Forward-burn gasification requires an open or highly-permeable link or pathway from the burn area to the production well. Repeated tries, during several of the Hanna phases, to get a forward burn to proceed out from a well-ignited injection well into either a virgin coal seam or a hydrofracked coal seam were never successful. This included attempts with multiple open wells available nearby for production.

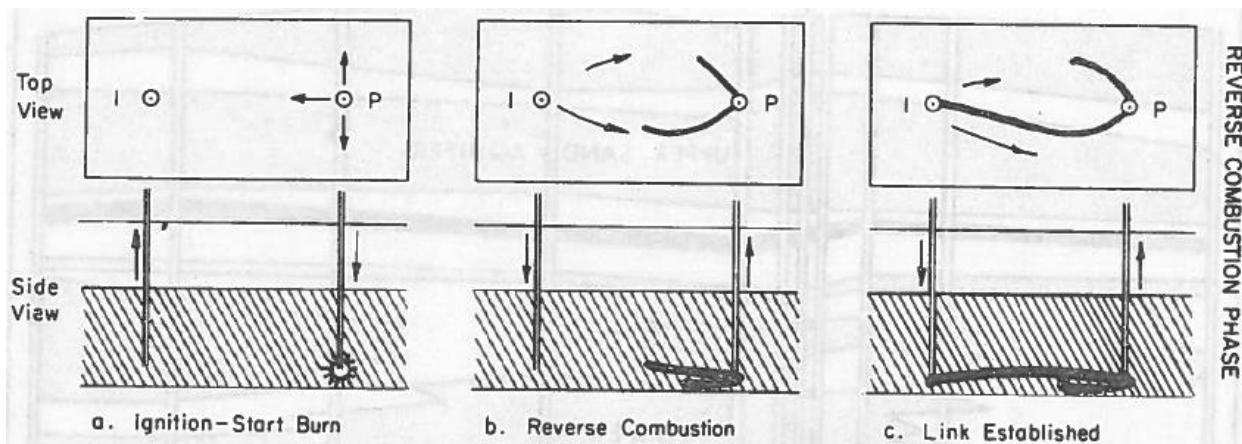
The corollary to this is that UCG forward burn in coal does not operate according to some of the early conceptual and mathematical 1-D “permeation” models of UCG (e.g. Gregg and Edgar, 1978; or Haynes, 1983). These imagine that forward burn proceeds like a Lurgi or packed bed gasifier, or a petroleum reservoir fire flood, with a series of fronts (combustion, gasification, pyrolysis, heating, drying, warming) moving through the virgin coal in the same direction as the product gases flowing ahead through the coal. It does not. Coal permeability is too low, and any flow would soon plug pores with condensed tars and water. Instead, around the edges of the open or highly-permeable rubble-filled cavity, heat conducts outward and the pyrolysis and drying fronts move outward, while fluids flow and pieces of ash, char, and dry coal fall inward into a more open or rubble-filled volume where gases mix, react, and find a relatively open pathway to the production well. (See Section 7.7).

Sufficient links were shown to include the following, and combinations there-of: an open borehole; a char-filled reverse-burn channel; an initial borehole or reverse-burn channel that has become full of char and dried-coal rubble and surrounded by fissured dried coal; an open burn-cavity volume; a burn cavity volume that is filled with rubble of ash, char, dried coal, and rock pieces; and an explosively fractured bed of rubblized coal.

The erroneous conceptual model of forward gasification contributed to the incorrect general assertion that high permeability was desirable for a UCG coal seam. Except for reverse-burn linking, high coal permeability is generally bad for UCG because of water influx, gas escape and groundwater contamination.

### 7.3 Reverse burn links

Many U.S. field tests used reverse burns to link and connect process wells and boreholes. An excellent simple sketch (Figure 40) and description of it appeared in a paper by principals of the Hanna and Rocky Hill field tests that used reverse burn links (Bell et al., 1983). “[After igniting the coal at the base of well P,] Air injection is then introduced to well I which causes reverse combustion links (RCLs) to propagate from well P towards well I. These link channels are not open conduits, but are very permeable regions of char, approximately 1 meter in diameter which form along the paths of greatest oxygen supply. More than one RCL may form and they may propagate at different rates ... Eventually, one of the links breaks through to injection well I. ... In practice, the idealized case does not usually occur. RCLs may follow irregular paths from one well to another. The flow path may rise to the top of the seam ...”



**Figure 40. Sketch of ignition and reverse burn linking, showing two wells completed into the lower zone of a coal seam. I and P are the injection and production wells for the reverse burn (and often but not always for the subsequent forward burn). (Bell et al., 1983)**

The U.S., particularly researchers at the Universities of Wyoming and Colorado did a considerable amount of theoretical and modeling work on reverse burn propagation especially in the earlier years of the program before the emphasis in the U.S. shifted to directionally drilled links. (Krantz and Gunn, 1983b). Formation of discrete and multiple channels could arise not only from the spatial variability of the permeability field, but were shown to spontaneously arise in a homogenous isotropic porous medium because of front instabilities with respect to fingering.

Experiences with reverse burn linking at all the Hanna tests, Hoe Creek II, ARCO's Rocky Hill, Pricetown, and Rawlins is documented, often in detail, in the field test reports. Reverse burns were even used to make short connections between wells/boreholes in some of the later tests in which the main link was a directionally drilled borehole. (Directional drilling at the time was not precise and sometimes holes missed intersecting each other by a few meters.)

The U.S. field test experience with reverse burn linking was mixed. Sometimes it worked smoothly, and a link could be accomplished in days or a week. Sometimes it did not go smoothly and required a great deal of fussing and trials, even in the hands of experienced operators. Hanna IV and Rawlins II had the worst experiences. Even with all the experienced personnel present at Rocky Mountain 1, using reverse burn to

make short connections between boreholes “was by far the most taxing phase in terms of the physical plant and personnel. … Startup and subsequent operation would have been much easier had mechanical connection of the wells existed …” (Cena et al., 1988a).

Good practice involved characterizing the natural preferred orientations of fractures, cleats, and permeability fields in the seam ahead of time, and aligning the wells accordingly, but results did not always follow the expected orientation. Links were preceded by pumping/blowing water out of wells, followed by air acceptance testing between candidate well combinations. Sometimes adequate connectivity was present and sometimes it needed to be enhanced by pneumatic or hydraulic fracturing. Fracturing sometimes produced unwanted permeability pathways.

The linking process itself always used air injection pressures that exceeded surrounding hydrostatic pressure. Sometimes product gas was observed to move out a long distance during this operation. The reversibility of this gas escape/bubble and the spatial extent, magnitude, and permanence of contaminant transport it caused depended on the details.

Links of different lengths were attempted, with and without pneumatic or hydraulic fracturing. Links up to 23 meters in length were usually successful. Links 30 meters and longer were not successful. Reverse links were sometimes enhanced by alternating forward periods by switching injection and production back and forth.

Reverse burns can be drawn from a large active burn cavity through the coal seam to a linking injection well. These tend to use more air and take more time per linear foot than pulling the burn from a small zone of ignited coal. When the source burn was broad and the injection air source was also broad and parallel to it across the seam, only one or a few narrow links will be made – a reverse-burn will not advance as a broad front.

Reverse burn linking was accomplished in a swelling agglomerating bituminous coal seam in the Pricetown field test. But the details were not as desired. The link(s) permeability was very low and was/were located at the top of the seam. Several alternating reverse and forward burns in alternating directions improved the link permeability sufficiently to allow forward combustion to be started, but the links plugged up again.

## 7.4 Directionally drilled links

MERC’s 1971 Longwall Generator Concept assumed the use of directional drilling to create long boreholes within the coal seam for delivery of injection gas along to a long burn cavity and withdrawal of product gas from the seam.

LLL’s Hoe Creek III field test in 1979 was the first of the U.S. program to replace reverse burn links with a directionally drilled horizontal borehole. (To improve the conductivity of the small diameter borehole and remediate any borehole caving, this first borehole was expanded by a reverse burn along its length, a practice not done in future tests.) Following this, all LLL, Gulf Oil, and GRI field tests (Rawlins II, both Centralia tests, and both modules at RM1) always used directionally drilled boreholes to provide in-seam links through the coal.

Continuing improvement in directional drilling control, distance, completion technology, and cost made it the linking method of choice. Scalable and high-efficiency process schemes such as CRIP and ELW evolved with the ability to create these links. Drilled links facilitate keeping both the injection points and product-gas pathway low in the seam and provide tight spatial control that will be beneficial for scale-up to multiple modules.

Proponents of directionally drilled links and especially its coupling with CRIP came to view the method of reverse burn linking, and its high pressures and oft-needed fracturing, as an ingenious and workable method that was no longer needed, except for making short connections between imperfectly placed boreholes and wells. With improvements in accuracy, these completions may be feasible with a simple water jet, or not needed at all. Directionally drilled boreholes have many engineering possibilities for completions designs such as the location and details of casing, liners, tubes, devices, and instruments.

## 7.5 Characteristics of the main forward burn phase of gasification

Given the preparation of a link between the main injection well and a production well, either by reverse burn or a drilled borehole (or even by explosive rubblizing), forward burn operations could always be established easily and reliably. In most field tests forward burn was an easier period than ignition and linking.

### 7.5.1 Forward burn is robust

Forward burn operations repeatedly proved to be very robust. They handled a wide turn-down range. Operations could be stopped for days, weeks, or months and resume quite easily. UCG operations in forward burn mode responded quickly, stably, smoothly and predictably to changes in injection gas pressure and composition, such as switching back and forth between air and oxygen-steam mixtures. They even tolerated major events such as collapsing volumes of roof coal and/or rock with only modest and conceptually reasonable changes in behavior. This is consistent with the nature of natural and mined coal fires – they continue for as long as oxygen is occasionally supplied.

### 7.5.2 Forward burn tends to ride up to the roof, requiring low injection point

The natural tendency of a forward burn is to ride up and consume coal near the top of the seam or in the upper half of the seam. Not only is this bad for resource utilization, it hurts thermal efficiency and gas quality (see Section 7.8). The best way to keep the burn from over-riding into the top of the seam is to assure that the injection point is at the bottom of the seam, and that it is moved to a new location at the bottom in new coal when heat losses to the roof significantly erode efficiency, and/or when it has stopped consuming coal around the low perimeter and is only consuming coal near the roof. The tendency to over-ride to the top of the seam might be improved some in the early phase of a burn by placing the linking channel low in the seam, and having the product well entrance near the bottom of the seam. This benefit is limited however, because even a drilled borehole link at the bottom of the seam has been observed to transition into a tall V cross-section with highest permeability and flow near the top.

In field tests where the performance was declining due to over-ride or excessive heat loss to the roof, performance was usually restored by moving the injection point to the bottom of the seam in ungasified coal.

### 7.5.3 Forward burn tolerates movement of the injection point

Given multiple wells, or positions within wells, that were connected by a link to each other and a mature forward burn associated with one injection well or point, a new forward burn can be initiated and grown at a different injection well or point by stopping injection to the first location and starting it at the second location. Sometimes this happened unintentionally, as when an injection well failed and the injection point moved from the bottom of the seam to a break near the top of the seam. In the Hanna series, the injection point and location of main burn were moved frequently as part of a plan or improvisation. This ability to switch locations of injection point was found to be useful in at least two ways.

If there is a mechanical problem with one injection well, another can be substituted to “rescue” an operation. The main injection well at Hoe Creek III plugged not long into the test, probably because of mineral slag from the high local temperatures during this oxygen-steam test. LLL adapted a well intended for dewatering into a new injection well and continued the process from there. This became, unintentionally, the first field demonstration of the borehole-linked ELW method. It was also a step along the evolution to CRIP.

If a burn from one injection point has grown and the cavity has grown vertically to have too much roof involvement, a new burn in new coal at the bottom of the seam will return process efficiency and gas quality to “new cavity” values. This was done at some of the multi-well Hanna tests and at the Centralia Partial Seam and Rocky Mountain 1 CRIP tests by using CRIP to open up a new injection point further upstream in a cased injection well.

## 7.6 The nature and evolution of the cavity and link

Most summary reports on field tests contain sketches of the best estimate of the cavity geometry. It is beyond the scope to reproduce them here. Singer et al. (2012) wrote a topical report dedicated to the cavity geometry results of field tests, and many cavity sketches are reproduced in Shafirovich et al. (2011).

Based on Hoe Creek drill-backs and the excavations at Centralia, Thorsness and Britten (1989c) describe the nature of cavities formed by bottom-seam injection to be, to a first approximation, symmetric with respect to the injection point, rubble filled, with nearly vertical walls. Refinement to this is that they grow about twice as fast in the direction of the product gas exit as in the backwards direction, and that they are perhaps more elliptical (vertical axis) than cylindrical.

In cross-section, perpendicular to the flow path, cavities are often taller than wide, especially in early stages when the cavity is still within the coal. In contrast to many of the sketches of UCG at the beginning of this program, the results from drill-backs of every U.S. field test of significant duration showed time and again that the cavity extended far up into the overburden, often by many or tens of meters.

Drill-backs of all the U.S. field tests and the Centralia excavations (Sections 4.7.3.2 and 4.7.4.2) consistently found that the “cavity” is filled with rubble, often with a small void volume near the top. This rubble consists of slag, ash, char, dried coal, and thermally-altered overburden rubble.

Cavity growth can be complicated, but was seen to be due to spalling, structural collapse events, and intermediate-scale fracturing and block falling. A main mechanism of growth of the cavity appears to be small-scale spalling, both sideways and upwards, and in the coal seam and in the overburden. Non-swelling coals and the sedimentary rocks overlying all the U.S. tests tended to spall upon heating and drying. The details may have varied, and likely included shrinkage and tensile fractures and fissures into which gas and heat conduct and enhance drying of adjacent material which then might fall in as blocks. Large collapse events were also occasionally observed and inferred. Some combination of structural stresses and weakening by fractures led to these.

Pieces of coal, char, and rock from spalling, block fractures, or larger collapse events fall into the cavity and form a rubble bed. This disperses the gas injected into the bottom of the pile. Gas reactions with the coal, char, and pyrolysis gases in this bed define much of the coal consumption, gas flow dynamics, and heat transfer in the system.

The spalling of coal and char pieces into a rubble bed is likely very good for UCG efficiency. But spalling of roof rock is bad because it increases the rate at which roof rock becomes heated, causing heat loss and water influx. An ideal site would have coal that spalls easily and roof rock that does not.

Exit channels that began as horizontal boreholes were discovered to evolve into a steep-sided upward V-shape cross-section with thermally-affected dried coal and char rubble filling the V. Permeability was greater near the top of the V channel. This presumably applies also to exit channels that began as reverse-burn channels of permeable char. Apparently downward movement was limited by thermal conduction. When coal above was dried and pyrolyzed, it apparently shrunk in volume, fractured, spalled, and fell, opening void and fractures above and outward.

## 7.7 A conceptual model for the UCG process

The field test observations and model calculations evolved into a conceptual model and scientific understanding of the UCG process. This is described well in the phenomenology sections of Stephens et al. (1982), Thorsness and Britten (1989c) and Britten and Thorsness (1989), and formed the basis for the CAVSIM model.

The outer boundaries of the cavity grow largely by thermal spalling, filling much of the cavity volume with pieces of dry coal, char, and rock. This rubble bed covers a low injection point and distributes injected oxidant through the bed, where it reacts with solids and pyrolysis gas to make heat and product gas. Heat transfer from the rubble bed and gas leaving it produces more spalling. Reacting gases mix in any open spaces, contact and react with coal side-walls and ceiling, and follow openings and rubble permeability to the exit channel. There they continue reacting until slow kinetics “freeze” the composition and heat the surrounding coal, pyrolyzing it and then pre-heating it. The pyrolyzed and dried char and coal shrink and become the rubble in the exit channel, which grows upward in a V shape.

## 7.8 Energy balance, heat losses, process efficiency, and gas quality

### 7.8.1 An energy balance governs process efficiency and gas quality

For a given coal the process efficiency and the product gas quality is largely determined by an energy balance. (c.f. Thorsness and Creighton, 1983). The two main losses are the heat used to dry and heat in-falling roof rubble, and the heat used to vaporize and heat in-flowing water.

### 7.8.2 Heat losses to roof rock involvement

In virtually every field test, for a given injection point and composition, thermal efficiency and gas quality started high and tapered down nearly linearly as the burn progressed. The decrease was associated with the gasification cavity reaching the roof. The decline of gas quality and thermal efficiency with the progress of the burn was probably due to roof involvement (heating and drying of cold wet roof rock as it fell in pieces into the burn). It may have also been due to permeation into the process from cracks in the overburden, as the cavity “ceiling” reached the roof and involved more and more roof rock.

If the roof rock stayed in place there would not be much heat loss from rock heating and drying because of the low thermal diffusivity of fine-grained rock. But all U.S. experience at the many field test sites is that the roof rock spalls, breaks, or structurally collapses into the cavity, or fractures in place and the smaller-size rubble pieces and fracture exposures will be dried and heated much faster. This is a significant loss term in the system heat balance.

Starting a new forward burn at the bottom of the seam in a new location within the same linked system was shown repeatedly to return the thermal efficiency and gas quality to near the original high values, and then taper off again with the progress of the forward burn from this new injection site as its cavity reached the roof.

These observations and energy-balance analysis are consistent with one of the most-repeated conclusions and recommendations for UCG in the U.S. literature. The injection point should be at the bottom of the seam. Another repeated recommendation is to minimize thermal involvement of the roof, and a site with strong, non-spalling roof rock would do that.

The fact that forward burns can be started in new locations (given that the locations are linked) provides the method whereby process efficiency and gas quality can keep being renewed to “new cavity” values. In the schemes of all the Hanna tests, Rocky Hill test, Hoe Creek III, and the ELW module of Rocky Mountain 1, multiple vertical wells are linked in the coal seam by reverse burn or drilling. The injection wells were switched from an “old” big cavity to a well completed in “new” (except for linking) coal to start a new burn cavity. Whenever the new injection point was near the bottom of the seam, the process was “rejuvenating” and its efficiency returned. The CRIP technology of Centralia and Rocky Mountain1, allowed the same thing to be done without separately drilled and completed injection wells.

### **7.8.3 Heat losses to water influx from roof rock drying, and from permeation**

Water entering the process must be heated, vaporized, and heated further to the product gas temperature where it exits. Water influx was often a major source of heat loss and diminished process efficiency. In terms of a material balance on the process, there are two sources of water influx – inward flow or permeation of moving groundwater into the cavity boundaries, and drying of roof rocks. Water influx from drying of roof rocks can not be differentiated in a material balance from permeation water, but the phenomena are different and they must be considered separately.

For most U.S. field tests, the combination of heat loss to heating of the mineral fraction of the roof rock plus the vaporizing and heating of the water fraction of the roof rock generally was greater than the heat lost to vaporizing and heating the inflowing permeation water. Stephens et al. (1985) put it this way, “Site selection plays a major role in gasification quality. Sites with relatively dry, strong overburden and at least moderately thick coal product favorable results. … Sites with thin coal or containing wet, weak overburden produce less favorable results....”

### **7.8.4 Cavity pressure, water influx, and gas escape**

Results from U.S. field tests show clearly that process efficiency and gas quality are correlated to water influx, which is consistent with energy balance analyses, both simple and sophisticated. Much effort was expended in the U.S. program to try to minimize water influx from permeation. The big conclusion is that for a given site water influx is inextricably linked to gas loss. Raising the cavity operating pressure will only reduce permeation at the expense of gas loss, and that the loss of recovered energy and especially the transport of contaminants that goes with gas loss is not worth it. Most field tests reported an observed increase in water influx with lower cavity pressures and more gas loss with higher cavity pressures. A state-of-art 2-phase (gas and water) unsaturated porous media flow model is highly recommended to understand this and find the best conditions.

The best practical way to reduce water influx by permeation without causing gas loss is to choose a site with low permeability coal, underburden (especially), and overburden. For a given permeability and a requirement of no gas loss, the other way to minimize water permeation in is to minimize the vertical extent of the gas-connected cavity.

## **7.9 Field test material and energy balances are difficult**

After over fifteen years of doing the most careful and detailed analyses of UCG data, Thorsness and Britten (1989a) write, “Material and energy balance closures are extraordinarily difficult in the analysis of UCG systems since the streams of coal, overburden and in situ water input cannot be directly measured.

Furthermore, an unknown fraction of the coal can be incompletely processed by being dried and pyrolyzed but not gasified. The energy content of the ash, char and overburden rubble depends on the local *in-situ* temperature, known only at a few discrete points at best, which may or may not be characteristic of large sections of the *in-situ* gasifier. Material balance estimates based on elemental balances and assumptions on *in situ* char composition can be algebraically unstable and large errors can result for small errors in measured rates and compositions of input and output streams.” In addition, coal composition is spatially variable and any average value is likely to be different than the volume of coal that was actually consumed. Their paper goes into details of material and energy balances, proposes and uses a new balance method based on nitrogen that appears to be better for oxygen-steam systems without much air nitrogen, and applies them to the ELW and CRIP modules of RM1.

Before this 1989 analysis, the LLNL way of doing material and energy balances was described by Cena et al. (1988a), Britten and Thorsness (1988), Thorsness and Cena (1980) and Cena and Thorsness (1981). Gunn (1979) laid out some early guidance for doing UCG material balances.

## 7.10 Gas composition

Product gas compositions from different UCG field tests vary quite widely, even from tests at the same site and often between different periods of the same test. McVey and Camp (2012) calculated the average dry product gas composition, weighted by mass of coal, for all the air-blown periods of U.S. field tests and for all the oxygen-steam-blown periods of U.S. tests. All field tests listed in Table 1 were included, from Hanna 1 through Rocky Mountain 1, with the exceptions of Rocky Hill, the Texas lignite tests, and the Centralia Small Block tests.

**Table 4. Tonnage-weighted average dry product gas composition (mol%) of almost all U.S. field tests done on bituminous or sub-bituminous coal from Hanna 1 through Rocky Mountain 1**

Species	Air-Blown	Oxygen-Steam
N <sub>2</sub> + Ar	53.87%	2.30%
O <sub>2</sub>	0.20%	0.00%
H <sub>2</sub>	13.49%	33.37%
CH <sub>4</sub>	4.50%	9.82%
CO	10.69%	9.82%
CO <sub>2</sub>	15.99%	42.08%
C <sub>2+</sub> HC's	0.45%	1.00%
NH <sub>3</sub> +NO <sub>x</sub>	0.60%	1.30%
S oxides	0.20%	0.30%

In the 1970's and 1980's, much effort was put into finding simple ways to predict the composition of the product gas from a UCG operation. Simple equilibrium and kinetic models were ineffective. Correlations were repeatedly looked for with little success.

There is no simple “UCG assay” that can be done on a coal to predict a product gas composition. This is because the composition of the product gas exiting from a UCG operation results from the entire detailed spatial and temporal history of reactive fluid transport, solid interactions, and thermal histories within the complex process. The two most sophisticated UCG process models, CAVSIM and UCGSIM3D achieved modest success by tracking many of these details.

Simple equilibrium models fail for several reasons. Typically, much more methane is seen from the relatively shallow (and therefore low pressure) UCG operations than a simple equilibrium gasification model would expect. This is because pyrolysis produces a lot of methane that ends up in the product gas without reacting. The amount of pyrolysis products that go into the product gas is clearly dependent on process flow details and temperature-composition fields. Water-gas shift species are rarely found in the ratio’s expected from temperatures in the main cavity. For each field test, there seems to be a different water-gas shift “set temperature” below which the kinetics slow enough to lock in a composition. This temperature appears to be affected by catalytic effects of the ash. The other factor confusing water-gas shift equilibrium is that water enters the process from several different sources at various locations along the process.

Some success was had with theoretically-based semi-empirical simple lumped-parameter models for estimating product gas composition, such as those described by Thorsness and Creighton (1983), EQSC (c.f. Upadhye, 1986), and UCGMEEE (c.f. Upadhye et al., 2013). These use material and energy balances and chemical equilibrium models applied to multiple “compartments.” But the calculations are modified and constrained by user-set adjustable parameters that have some basis in reality. Typically, the user specifies system factors such as the amounts of water influx and heat loss, and product gas exit temperature. Also specified are empirical factors including a parameter related to methane abundance that over-rides methane equilibria, a water-gas-shift equilibrium temperature, and the fraction of water influx that participates in reactions (compared to water entering the process downstream of where the gas is hot enough to react).

## 7.11 Extended Linked Vertical Wells

The Extended Linked vertical Wells (ELW) method was one of the two methods fielded at Rocky Mountain 1. Various configurations are possible that make use of a long in-seam borehole near the bottom of the seam to be used as the link between one of many injection points and burn locations, and the production well. Multiple vertical injection wells, completed to the bottom of the seam, intersect at intervals with the in-seam borehole link.

With reverse burn links between vertical wells instead of long drilled boreholes, several of the Hanna tests and the Hoe Creek II test could be construed as early examples of ELW. Hoe Creek III pioneered borehole-linked ELW in the U.S. when it switched back and forth between two vertical injection wells that intersected the drilled horizontal borehole that linked some distance away to the casing of the production well.

In the case of Rocky Mountain 1, the first injection well was at the distal end of the open borehole, with product gas flow going back along the open borehole to where it is completed as a production well. After this first cavity grows until the heat loss to roof involvement hurts efficiency, injection is switched to the next injection well located downstream along the product gas pathway and a new burn is started there.

The poor performance of ELW at RM1 was largely due to the incorrect completion locations and should not in itself be damning to ELW. The greater concern for ELW as with any vertical well technique are

how to design the well to survive, given its location at the hottest and tallest extent of overburden collapse, as well as the economics of drilling frequent vertical wells at the larger depths required for environmental isolation. Wider spacing to reduce well construction costs will incur longer-operating cavities and higher cavity growth into the overburden.

### 7.12 Controlled Retracting Injection Point (CRIP)

Probably the most outstanding, useful, and enduring product of the entire U.S. UCG effort was the invention of the Controlled Retracting Injection Point (CRIP) technique. CRIP provides positive control of the gasification process, a means to extend the process spatially into successive volumes of new coal while keeping the injection point low in the coal seam, roof involvement low and efficiency high.

The abstract of its first publication in the 7<sup>th</sup> UCG Symposium (Hill and Shannon, 1981) reads as follows. "The underground coal gasification process, in practice, is subject to various problems that make it difficult to maintain and control an efficient long-term operation. One of the major problems is the need to move the injection point (where the combustion-supporting air or oxygen from the surface is fed into the coal seam) to new areas of unburned coal as the burn progresses. To achieve better control of the gasification process, we recommend the controlled retracting injection point or CRIP system. With this technique, the operator can choose the optimum time and distance to move the injection point, and consequently the burn zone, to get the best possible performance from the gasification process." The essence of CRIP was illustrated in Hill and Shannon's original paper (1981), shown here in Figure 41. A good later excellent description of CRIP is found on page 6 of Thorsness and Britten (1989c).

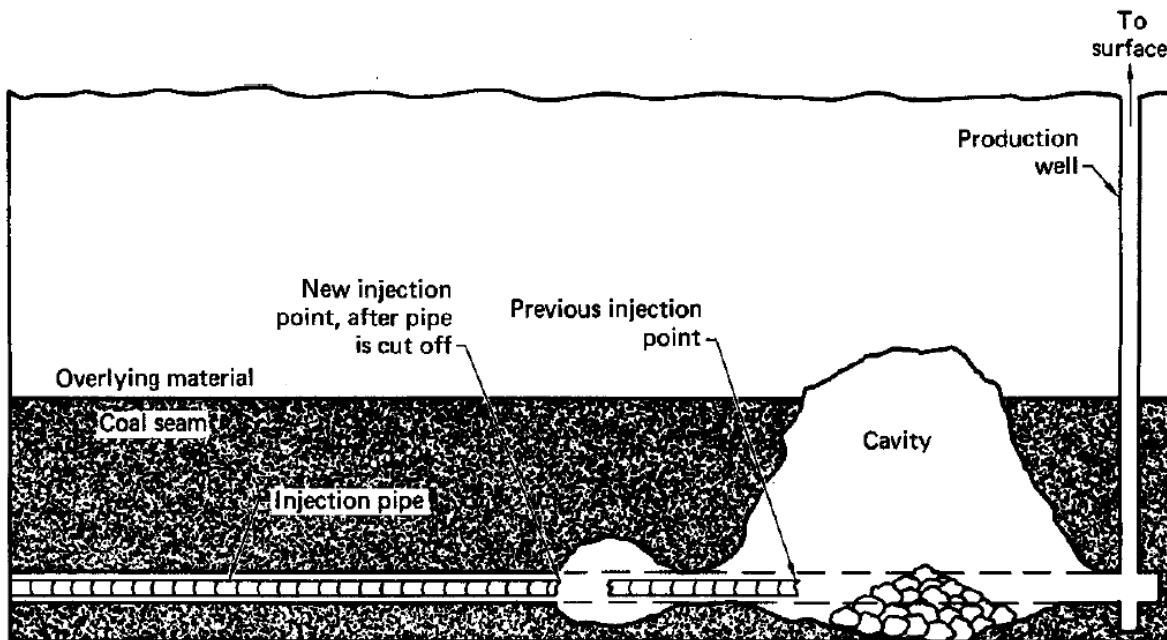


FIG. 1. Basic design of the controlled retracting injection point (CRIP) system. As the cavity burns toward the left, the injection point is moved to the left also, step by step, by cutting off or perforating the injection pipe, which can be done remotely from the surface. Thus the injectant gas is always being fed to a zone of the coal seam where unburned coal remains to be gasified.

Figure 41. Hill and Shannon's original sketch and description of CRIP. (Hill and Shannon, 1981)

CRIP was conceived and developed by the Lawrence Livermore Laboratory team after its Hoe Creek field tests, which showed, consistent with observations from LETC's preceding Hanna field tests, the importance of keeping the injection point low in the seam, the viability of a directionally-drilled borehole to be a link, and the benefit of being able to inject at different points along such a borehole into new coal to create successive "young" cavities.

Given a long extent of cased or lined injection well in a coal seam, the CRIP technique provides a way to ignite the coal at the end of the lined portion, inject the main air or oxygen-steam to the coal at that point, start and continue a burn cavity at that point, and then later melt a hole in the liner at an upstream location, ignite the coal there, inject there, burn a cavity there, and continue repeating this process. In a horizontal seam, the injection well would be drilled along the bottom of the seam to always assure the injection point would be low in the seam.

The configuration is essentially the same as what was done in the Hoe Creek 3 field test, except that the CRIP injection well and two illustrated injection points have replaced HC3's vertical injection wells A and P1. This figure also shows exactly how CRIP was first demonstrated by in a coal seam in the field at Centralia in LLL's Large Block test number LBK-1. While this sketch shows CRIP being used in what has now become known as "Linear CRIP" configuration, the technique has never been wed to this geometry; from the beginning CRIP was intended to be useable in a variety of configurations.

"There are several possible geometries for the gas production well. [As shown in Fig. 1.]; or one can use another horizontal hole in the seam, parallel to the injection hole ... A third possibility, with particular application to thick seams, is a horizontal [production] hole at the top of the coal seam, vertically above the horizontal injection hole [well].” (Hill and Shannon, 1981) Original sketches of these, with captions, are shown in Figure 42. They describe how these can be scaled up to long injection well lengths and arranged parallel to each other with the spacing set by trading off resource recovery against subsidence.

LLL's Partial Seam CRIP field test (PSC) in Centralia, Washington, provided the first sizeable field test demonstration of CRIP. This was deployed in what is now known as "Parallel CRIP" configuration, similar to Figure 42-top but with only one production borehole and angled to intersect the injection borehole instead of the right-angle shown. Based on the PSC's success, Rocky Mountain 1's CRIP module also used CRIP in the parallel configuration. While not needed in theory, the practice at that time for Parallel CRIP used a vertical production well to get the process initiated, and the first cavity is begun in the linear configuration. Sketches of how CRIP was used in the LBK-1, PSC, and RM1 tests are shown in their respective sections of this report.

Thorsness et al. (1988) describe in detail the tool and procedure used in the Rocky Mountain 1 field test to perform a CRIP maneuver. Briefly, this uses a silane torch to melt the steel liner and ignite the coal at a new location. When not in use, it is retracted a distance up the injection well out of harms way. When a CRIP maneuver is needed, it is pushed out to the desired position, operated, and retracted again.

The use of CRIP in UCG processes has many possibilities and will need to be optimized. As detailed in Section 4.8.4.1, the liner in that experiment tended to melt back on its own to some extent. This could be eliminated with a higher-temperature material, encouraged with a lower-temperature material, or made to burn back periodically on its own by placing low-melting sections periodically (a tried and abandoned Soviet concept mentioned in Hill and Shannon).

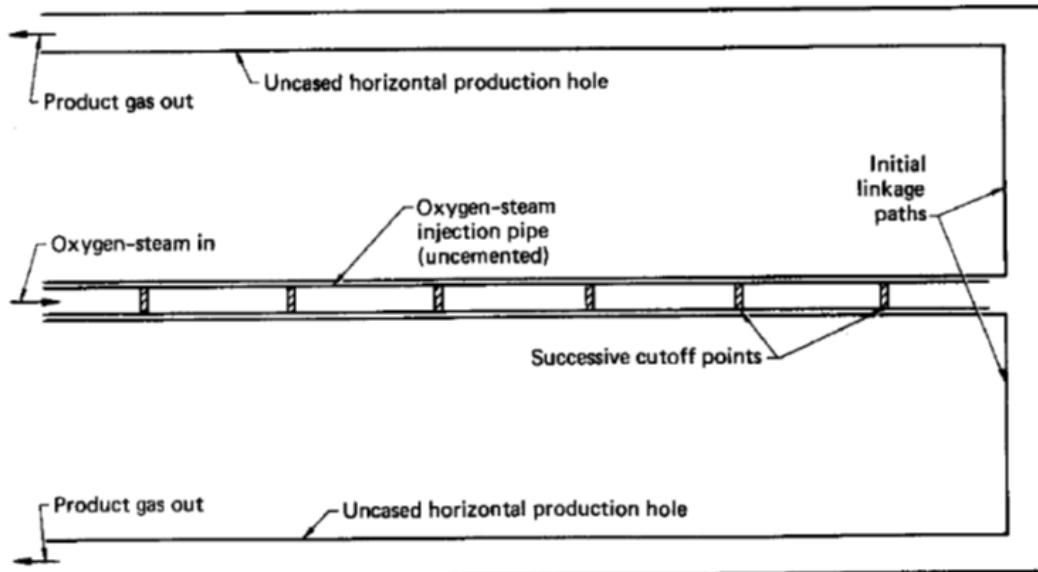


FIG. 3. Plan view of stream method adaptation of the CRIP system, with both injection and production holes drilled at the bottom of the coal seam. This version would be advantageous for dipping seams where slag accumulation in the bottom of the cavity might plug a down-dip production well.

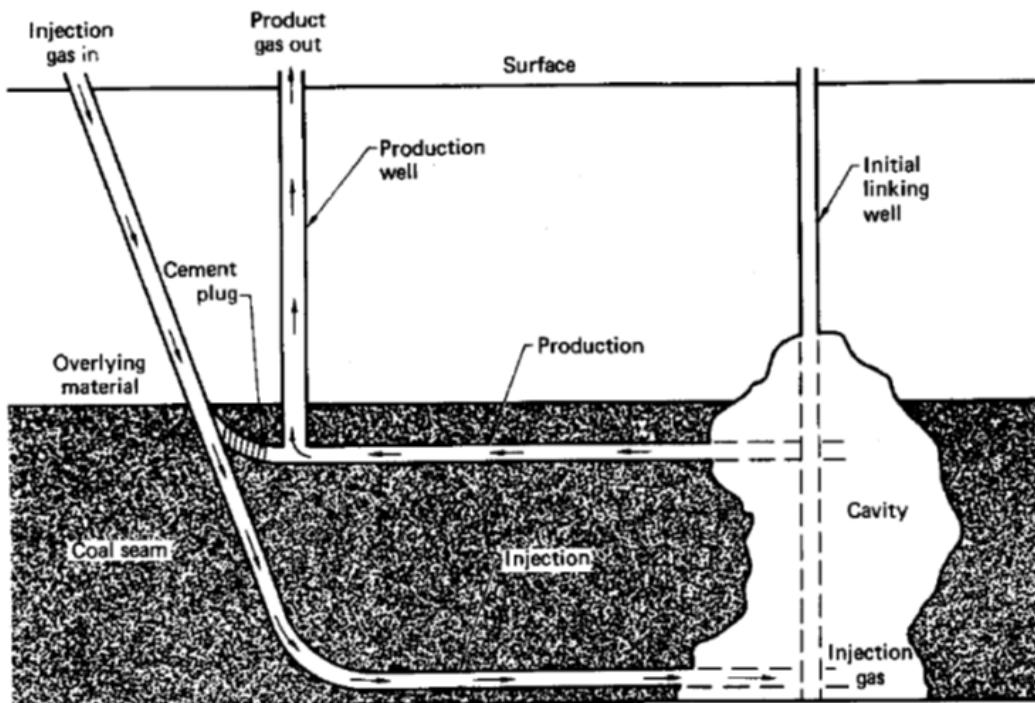


FIG. 4. Vertical cross-sectional view of a module of a commercial CRIP system, in which the injection hole is at the bottom of the seam, while the production hole is at the top of the seam.

Figure 42. Hill and Shannon's original illustrations and descriptions of: Top: what now would be called double parallel CRIP; and bottom: vertically-stacked parallel CRIP. (Hill and Shannon, 1981)

### 7.13 Steeply dipping beds are efficient but risk gas loss

UCG in steeply dipping beds will tend to be thermally more efficient than in flat beds. Burns and cavity growth tend to go upwards, largely because overlying spalled material falls from its location down into the burned cavity. In a steeply dipping bed, such a cavity will have a higher ratio of coal consumption to thermal loss to roof rock. The high heating values obtained in the steeply dipping Rawlins I-air and Rawlins II tests and the very thick seam Rocky Hill test demonstrate this.

Steeply dipping beds make it more challenging, if not impossible to avoid up-dip gas loss and its associated transport of contaminants towards the surface where pollutant receptors are more sensitive. In many basins, including essentially all of those used in the U.S. program, the coal seam is the stratum with highest permeability. The rule for preventing gas escape and associated groundwater contamination is to keep the pressure in the cavity below that of the water-saturated surroundings at the highest elevation at which gas is pneumatically connected to the cavity. This is a challenge for cavities that have a large vertical extent and a fast and difficult-to-measure vertical growth rate. If the pressure is conservatively low to assure no gas escape at the top of a tall cavity, then the driving force for water influx at the bottom of the cavity will be large. This will tend to make inward water permeation at the bottom of the cavity large which hurts efficiency. This depletes groundwater at a greater rate and deepens the “cone of depression” of the system, further reducing the pressure at which the cavity can be operated. If the pressure is operated closer to the pressure of the surroundings near the bottom, it will be over-pressured near the top, allowing gas to escape.

Product gas escaped up the seam to the surface at Rawlins, as evidenced by carbon monoxide readings. Even the 7-degree dip at Rocky Flats enabled a few days of high-pressure operation to push gas many hundreds of meters up dip.

### 7.14 Thick seams are efficient but risk subsidence and gas loss

UCG in thick seams will tend to be thermally more efficient than in medium or thinner seams. It will also tend to be more at risk of gas escape and associated transport. The reasons are qualitatively the same as described above for steeply dipping beds, with a few adjustments.

Thick seams have the potential to be even more thermally efficient than steeply dipping ones because the ratio of roof heat loss can be even lower, and the vertical extent is likely to be less, meaning less water influx at the bottom.

If there is gas escape in a horizontal thick seam, it will tend to be mainly lateral if the coal seam has higher permeability than the overburden strata. Given a deep seam, this will affect sensitive pollutant receptors near the surface less.

Thick seams may be more environmentally challenging because the vertical extent of roof collapse (goafing) is likely to be greater. This can open up gas connectivity far up into the blocks and fractures of a collapsed overburden, making product gas escape up to shallow strata more likely. Sorting this out will take a sophisticated level of mining engineering. The simple solution for environmental protection would be to leave enough coal pillars to minimize wide-scale tall roof collapse, but the economic penalty for this is low resource recovery.

Even though just a 3300 Mg field test, there was a very high extent of roof collapse and fracturing at the thick-seam Rocky Hill test.

## 7.15 Monitoring of UCG operations and cavity evolution

The philosophy of the government-funded UCG program recognized that for UCG to be effectively developed into an efficient large-scale industrial process, it had to be understood. Understanding requires detailed knowledge of conventional chemical process parameters such as flow rate, composition, pressure, and temperature. Understanding also requires knowledge of what the process is like underground – how the cavity grows and what is it like, where the fluids flow, how the temperature field evolves, etc. A great deal of effort was spent on this and it was valuable in understanding the process.

All the U.S. UCG field tests made measurements of the standard chemical process parameters. LLL was especially diligent in always having a state-of-art custom real time data acquisition, storage, and plotting display capabilities. These allowed trends and problems to be seen in real time. Relevant data and correlation plots could be pulled up in real time to inform the analysis of a situation and guide real time process decisions. The data were intensively used in the months and years following to discern trends and correlations evaluate and calibrate models, and perform detailed material and energy balances over selected informative time periods. This strength continued through to RM1, where LLNL was responsible for installing the real-time data acquisition system, in training operators in its use, and advising difficult operational decisions.

In addition to hydrology monitoring and sampling, Mellors et al. (2016) summarize the RM1 process monitoring as consisting of “9 instrument wells, 114 temperature sensors, 24 flow meters, 23 pressure transducers, 15 analytical instruments and 5 level detectors.”

A great deal of effort was spent in most tests to learn the geometric evolution of the cavity and, for reverse burns, the location(s) of the channel(s). Test instrumentation included thermocouple strings in wells, extensiometers, strain gages, and in-situ tiltmeters, time-domain reflectometry, microseismic/geophone installations, high-frequency (1 to 100 MHz) electromagnetic imaging (HFEM), controlled-source audio magneto-telluric measurements (CSAMT), and others. They are described in detail in topical reports, often presented in the annual UCG Symposia, and summarized in the original summary reports on each of the field tests.

The general and much-repeated conclusion in field test reports was that no one method provided a complete picture, but that by piecing together incomplete information from multiple different methods some information could be learned during the test about how the cavity was evolving. For the small-scale field tests, it seemed the most used and most informative methods were thermocouple strings in wells and HFEM.

A section of LLNL’s Best Practices document (Burton et al., 2008) makes some recommendations regarding monitoring techniques. In recent years the LLNL team reviewed monitoring techniques used in the past and explored two new possibilities, downhole electrical resistance tomography (ERT) and INSAR, in some detail (Mellors et al., 2016).

To date the most effective way in most circumstances to really know the nature and shape of the final cavity is to drill-back into it after the operation has concluded. Drill-backs were common for most all the field tests and provided a wealth of information of the shape and contents of cavities. Careful inspection and even forensic mineralogy examination can provide a good description of the composition, particle size, mode of formation, and temperature history of the overburden rock and cavity contents recovered from drilling. Most summary reports on field tests included sketches of the final cavity that were consistent with all known information including material balance, thermocouples, real-time geophysical monitoring, and post-burn drill backs.

Centralia's UCG operation at the face of a seam in an active surface mine provided a unique opportunity to excavate the cavities and product gas linkage path slice by slice. This direct physical observation proved extremely valuable for understanding the process better. In addition to geometric measurements and visual observations, samples were taken for later detailed examination. This provided an outstanding and unimpeachable description of cavity geometry, nature and temperatures.

These monitoring and post-burn characterization efforts informed workers conceptual model of how UCG proceeds and consequentially guided mathematical model development. The data taken also have value for validating and calibrating models.

## 7.16 Technical maturity and scale-up

The U.S. program demonstrated UCG's feasibility at the single- or few-cavity scale up to about 10,000 Mg. Several technologies of well design and linking were shown to work successfully, and forward burn operations were generally robust. But even after dozens of tests at this scale, UCG design, construction, and operation had not become routine. As late as Rocky Mountain 1, experienced operators were not able to have the project and operations go smoothly. UCG was still young in its maturation.

Very little progress was made towards scale-up to industrially-relevant operations large enough to affect the U.S. energy supply picture. The many sketches of how UCG techniques might be scaled up by adding multiple modules were never tested. Nor were they given a detailed geotechnical design that would look quantitatively at geomechanical aspects such as roof collapse, goafing, room-and-pillar resource recovery, and subsidence (not just at the surface, but of the strata that provide environmental isolation) or hydrological aspects such as groundwater depletion, multi-module interactions, gas escape.

Technologies and approaches that would facilitate scale-up were conceived and tested. Directionally drilled boreholes and wells for linking and gas injection/removal were tried successfully. CRIP was invented and has excellent potential for scalability. The feasibility of using reverse burns to link new process wells to existing burn cavities was done successfully.

One of the biggest problems needing more development is the design and construction of well completions. There were many failures from heat, structural failure, leaks, failure to not inject into the bottom of the seam, and in the grouting between the well and the formation. Mundane process engineering technologies, such as particulate erosion of pipes, were also still a challenge and needed maturation.

In summary, at the end of the U.S. program, UCG remained low on the development curve towards routine operations at large scale.

## 7.17 Economics

DOE funding in the 1970's and 1980's had the goal of developing technology to hand off to industry for large-scale cost-competitive energy production. Hence most of the institutions doing research made various estimates from time to time of UCG's economics. Even many of the technical reports reporting field test progress included a section on projected costs at large scale. Invariably these were optimistic and did not adequately account for technology development and maturation costs, the costs of environmental protection and permitting, or full project facilities and engineering costs. They are ubiquitous in original reports of this era, but are not reviewed specifically here. As an illustration, an especially optimistic comment is found at the end of Lamb's (1977) section describing the very first U.S. field test, Hanna I. "A second experiment to further define process feasibility, if successful, would lead to

design and construction of a 15- to 30-Mwe pilot plant, and successful pilot plant operation would lead to design of a commercial demonstration plant by 1980.” It is unclear if this is Lamb’s opinion or if it originated in a LERC report or conversation.

Following a brief review of UCG basics and short synopses of U.S. and international field tests, the GasTech (2007) paper study details a notional large UCG project in Wyoming’s Powder River Basin, including infrastructure, balance-of-plant, environmental characterization and preservation, and permitting. It includes cost and economics estimates.

LLNL’s UCGMEEE model makes use of the GasTech cost study and scaling rules to estimate cost and economic factors for a postulated UCG operation. As described in Section 6.3, it requires inputs that can not be known well without a detailed design, serious modeling of various aspects, and/or data from experience with a similar design at similar scale in the same location.

## 8 Environmental aspects

### 8.1 Groundwater contamination

United States field tests demonstrated repeatedly that the risk of groundwater contamination from UCG is real. The Hanna tests resulted in small amounts of contamination. Relatively minor remediation was needed at two of the four Hanna test areas. The Hoe Creek tests, especially Hoe Creek 3, seriously contaminated the site, requiring an extensive expensive remediation. The reported gas escape, large upward extent of cavity growth, fracturing, subsurface subsidence and overlying aquifer at Rocky Hill must have spread contaminants although ARCO’s paper on this test did not say so. There was upward transport of product gas to the surface in the steeply-dipping coal seam and in the periphery of a well at Rawlins. The extent of research on UCG-produced contaminant species by Texas-based workers of the time (c.f. Humenick and Mattox, 1978, 1982) suggest it was a concern in the Texas lignite tests. Rocky Mountain 1 lost about 10% of its gas overall, and early in the test it spread product gas hundreds of yards up dip, exceeding contamination limits, during their high-pressure reverse-burn connecting operations. Williams’ short-lived Carbon County testing at greater depths in the steeply-dipping G seam near Rawlins operated at pressures higher-than-surroundings and contaminated groundwater in the seam and overlying and underlying sandstone units with benzene and other organic compounds, requiring remediation. There were significant differences in observed groundwater contamination between tests, with only minor changes in groundwater over limited areas found and reported after some tests and serious contamination over broader areas following other tests, with imperfect correlation to operating practices and estimated gas losses.

Factors that contribute to groundwater contamination were generally known at the beginning and early phases of the main U.S. field test program, but they appear to be given lower priority over technical success, process efficiency, industrial safety, and project costs. Ironically, the early environmental failures (at small scale) motivated work leading to improved approaches for operating more cleanly. As the reality and importance of minimizing groundwater contamination impacts became more apparent, more attention was devoted to this, resulting in a greater understanding of the processes and the development of mitigating practices. Much of this work centered at WRI (c.f. Covell et al., 1988 and Boysen et al., 1988, 1990), but also included Texas researchers (c.f. Humenick and Mattox, 1978, 1982), North Dakota Mining and Minerals Resources Research Institute, GRI, LLNL, and others.

By the end of the main phase of the United States' UCG program, the collective understanding of groundwater contamination mechanisms and scenarios included:

- Acceptance that pyrolysis occurs in UCG, it produces many toxic organics, and unlike the high-temperature surface gasification processes, a large fraction of them are not completely converted to simple gases
- Improved understanding that inorganic contaminants can result from secondary processes driven by higher temperatures and/or geochemical changes such as pH change from increased CO<sub>2</sub>, NH<sub>3</sub> or SO<sub>x</sub> concentrations.
- Gas escape from the process is the primary vector for transporting these contaminants away from the process, although the lower-volatility and water-soluble contaminants will condense or dissolve into less-mobile groundwater along the way and not go out as fast or far as the gas itself
- Gas will tend to escape if the process pressure exceeds the surroundings, and/or if the coal seam has a significant dip. The magnitude of the escape will be greater if the seam and surroundings have high permeabilities or high permeability paths
- UCG cavities can grow upward a long distance into the overburden, with fractures extending above those, and these will bring contaminant-laden UCG process gas at the cavity pressure to these higher elevations where the surrounding hydrostatic water pressure is lower.
- Drawdown (cone of depression) from water flowing from the surroundings into the process cavity can reduce the water pressure of the surroundings, and, if the cavity pressure is not correspondingly reduced with time, the cavity pressure will exceed that of the changed surroundings.
- Gas can also escape to shallower surroundings by flowing up uncemented boreholes, the outside of poorly grouted boreholes, natural faults, and permeable pathways such as dipping permeable strata or coarsely-filled stream beds
- Gas can also escape to shallower surroundings (which have lower hydrostatic pressures than the deeper cavity operating pressure) by leaking at joints or failure-points from wells that are open to the cavity but closed or restricted at the surface, including the main production wells and instrument wells
- Char, coal, and carbonaceous species in sedimentary strata tend to adsorb organic contaminants, which can greatly retard their transport by both gas and aqueous flow
- Transport of low-solubility contaminants by groundwater flow is slow and retarded by adsorption

By the time of Rocky Mountain 1, this understanding combined with laboratory experiments, modeling, and good thinking about the problem, led to a set of recommendations called the Clean Cavern Concept. Mainly advanced by WRI researchers, these made sense and were adopted by the RM1 management and facilitated successful permitting. (Covell et al., 1988 and Boysen et al., 1990). Clean Cavern recommendations included maintaining cavity pressures below the hydrologic confining pressures, post-burn venting and steam flushing of cavities to evacuate pyrolysis vapors, cooling of the cavity to minimize further pyrolysis, and assuring subsequent inflow and production of groundwater from the

cavity. Except for the pressure excursions of reverse burn connections and their and associated small contamination levels, the RM1 test followed these rules and had low magnitudes and spatial extents of contamination.

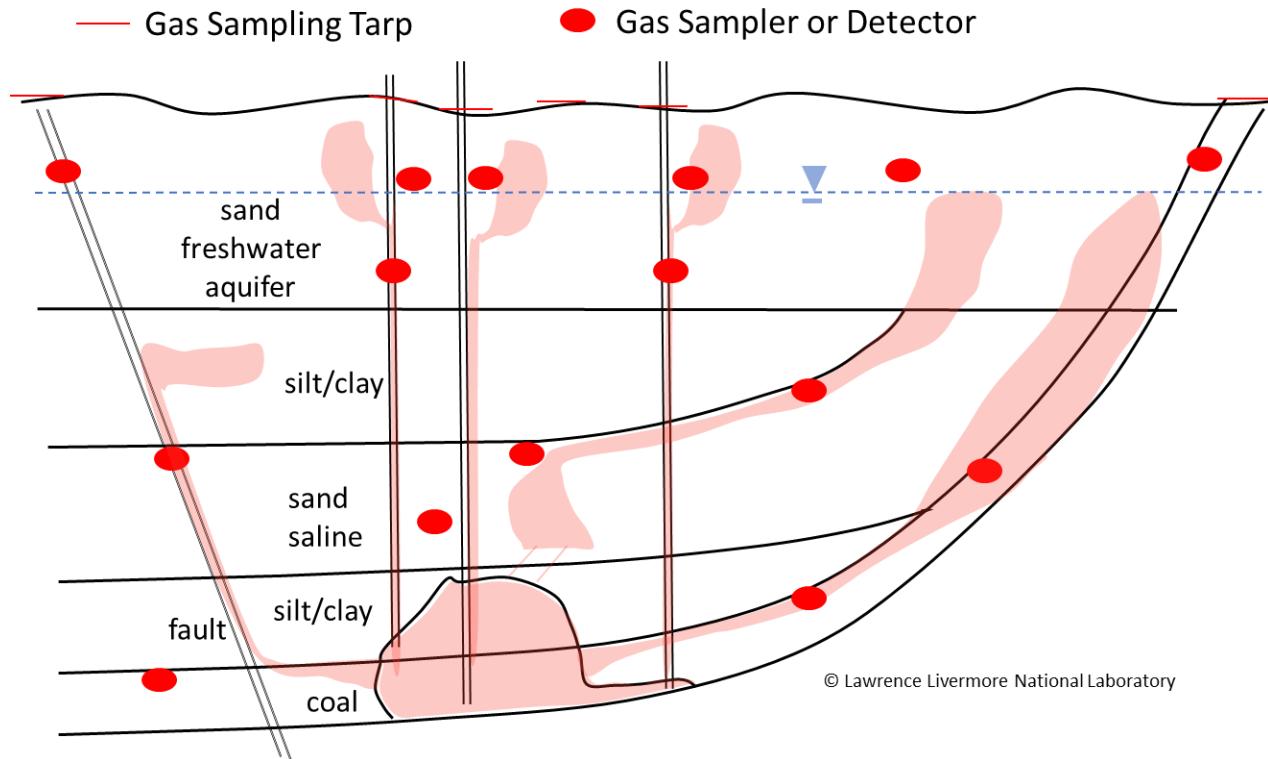
By the end of the main U.S. program, there had emerged a consensus that the following activities and choices would reduce the risk of unacceptable groundwater contamination. These are consistent with the Clean Cavern procedures but are broader in scope and stated more generally:

- Choose a site that minimizes the exposure to sensitive environmental receptors. This means minimizing
  - Nearby, downgradient, and up-dip uses of groundwater and surface water
  - Proximity to potentially-useable aquifers
  - Proximity to residences, businesses, and recreational activities of people, and of valued animal habitats
- Choose a site that has barriers to transport of contaminants from the immediate and contaminated UCG process area to sensitive environmental receptors, and do not create or increase transport pathways
  - Deep, far from the surface
  - Low permeability coal seams and strata that will be in contact with the coal seam
  - Wide-extending and reliable low-permeability strata(m), located above the highest-possible zone of fracturing above the UCG cavity and any sensitive shallower receptors such as potable aquifers
  - Seams and cavity-contacting strata that are horizontal or very low dip
  - No/limited faults
  - No uncemented or poorly-cemented boreholes
  - No operations, such as non-localized fracturing, that would increase the permeability of formations that are part of the needed transport barrier
- Assure no leaks of process gas from instrument or process wells into shallower strata
  - Design and quality-assured construction of both the casing/liner(s) and external grouting to not leak under pressure, even after erosive corrosive gas flow and with thermal expansion and mechanical stresses from ground movement
- Assure during operation that the pressure in all gas volumes that are connected to the cavity is lower than the water pressure in the surroundings at all adjacent elevations (i.e. at the elevation of the highest gas-connected fracture)
  - Minimize the upward extent of cavity growth, including fractures in the overburden that are big enough to drain water and fill with process gas at cavity pressure

- Control the cavity pressure below the water pressure in the surroundings; this includes at the highest elevation of the gas-connected fractures above the cavity, and at later times when drawdown has reduced the pressure in the surroundings
- Monitor the cavity and fracture growth and the fluid pressure field in the surroundings by a combination of measurements and modeling, and use this information to inform decisions on cavity operating pressure
- Deploy methods to detect gas escape from the cavity and use early detection of gas escape to quickly make process adjustment and reduce the distance contaminants are transported
- Minimize the quantity of contaminants left underground in and near the cavity and exit product pathway
  - Gasify later in the process those areas in which tars accumulate early in the process
  - Use something like the Clean Cavern Concept's shut-down protocol to minimize further pyrolysis and maximize the up-well production of contaminant species
  - Continue producing steam and water from the site, with controlled hydrology, until contaminant removal has become negligible
- Characterize groundwater and pore gas in the immediate process area and the surroundings, especially in/near aquifers and sensitive receptors before operations begin, during, and afterwards for several years.

Owing largely to its government sponsorship, the problems, understanding, and recommended approaches relating to groundwater contamination were documented in publicly available symposia proceedings and reports. This made it possible for the international UCG projects that followed in the 1990's and 2000's to take advantage of this information for their design, construction, and operations.

Groundwater contamination was a major area of emphasis in LLNL's recent (2004-2015) UCG program. Burton et al. (2008) summarize the Hoe Creek investigation and made general recommendations for cleaner practices. Camp and White (2013, 2015) describe the phenomena involved with groundwater contamination, contaminant transport scenarios and pathways, and practices to minimize the magnitude and spatial extent of contamination and its impacts. They add generality to the operating pressure rule, calling attention to the factors of upward growth of the cavity and its gas-connected fractures, aquifer pressure reduction from draw-down, and the requirement that gradients be inward. They also suggest that gas escape will likely occur as a fast- and far-traveling finger(s) instead of a broad front. Temperature, condensation, and solubilization fronts are calculated semi-quantitatively and sketched. The importance of frequent monitoring and modeling of unsaturated hydrologic flows and the overburden cavity/fracture field are stressed. The utility of gas detection and sampling for early far-field detection of escaping gas is recommended. Figure 43 summarizes some of the phenomena, pathways for transport, and opportunities for early detection of potential contaminant transport.



**Figure 43. Possible UCG contaminant transport pathways and opportunities for using gas detection or sampling to discover them early. (Camp and White, 2015)**

## 8.2 Gas loss

Material balances, tracer tests, and other observations (c.f. Cena and Thorsness, 1981; Cena et al., 1988a; Bell et al., 1983; and Davis, 2011) indicate that losing 10-20% of the produced gas was common throughout the entire field test program all the way through RM1.

Gas loss would be expected to increase with higher operating pressures (relative to surroundings), vertically higher extent of upward cavity growth and connected fractures, greater drawdown of pressure head in the surroundings, steeper dip, the presence of leak paths such as up the outside of wells or leaks out of wells, and greater permeability in the coal seam or overburden strata, including permeability induced by hydraulic or pneumatic fracturing and by overburden subsidence strains. Many of these trends were observed in field test data, but there were exceptions.

## 8.3 Subsidence and changes to the overburden permeability field

Roof collapse and subsidence were analyzed in the main era of UCG research and in LLNL's recent (2004-2015) UCG program. As with removing coal from the underground by mining, UCG can cause overburden to collapse, rubblize, fracture, and strain. One unwanted outcome of this is surface subsidence. Management of this would follow mining industry practices, for example like those of either room-and-pillar or longwall mines. A key difference, however, is the lesser degree of control over and knowledge of material removal geometry.

Long before there is much surface subsidence, collapse, movement, fractures, and strains underground are likely to change the permeability field. With a small single cavity, even one that has eroded up into the overburden, there may be a compressive arch over it which would tend to reduce permeability in the arch compression zone and provide a protective barrier against contaminant transport. But such an arch may not occur or may not be complete. In large-scale UCG operations, it is more likely that higher permeabilities would be created a long distance above the seam. To isolate the UCG operation environmentally from shallower sensitive contaminant receptors, the extent of permeability enhancement must be estimated to assure there is an impermeable barrier above it before surface aquifers are reached.

The general recommendation is that modern geotechnical modeling and engineering must be used to help assure that UCG operations don't affect the subsurface above them in unacceptable ways. This will need to be informed of the data available from field tests that found very tall cavities extending up into the overburden. Because of the contamination risks, these analyses will be more critical and demanding with UCG than with mining. UCG poses the added difficulties of thermally-accelerated spalling or caving of the roof, and lesser control and knowledge of cavity geometry.

Room and pillar type designs may provide better protection against a large vertical extent of overburden changes. But the resource recovery from these will be smaller than from a longwall approach with its large-scale goafing.

## 8.4 UCG and greenhouse gases

LLNL's recent UCG program in the 2000's was motivated in large part by a perceived opportunity to reduce emissions of carbon dioxide (Section 2.3.3). Effort was devoted effort to understanding UCG's advantages and disadvantages with respect to greenhouse gas emissions.

Well-run UCG field tests in favorable locations have shown efficiencies approaching those of surface gasification. It is reasonable to predict that more-developed and larger-scale UCG operations may have energy efficiencies that are comparable to efficient surface gasifiers, especially if the energy used in mining, processing, and transporting coal is counted.

Energy from coal fundamentally produces more carbon dioxide per unit energy than most other energy sources. If the same amount of coal will be used anyway, UCG, like surface gasification, may offer some advantages that are discussed next. If UCG tilts the energy mix toward more coal and less other sources, then this creates more carbon dioxide that will either enter the atmosphere or add to the amount that must be captured and sequestered.

Gasification is technically amenable to separating and capturing carbon dioxide which could then be sequestered. This has been advanced with recent designs, development and demonstrations with surface gasifiers. The utility of this at a scale large enough to matter assumes that sequestration technology matures and becomes accepted. Utilizing carbon dioxide, as with enhanced oil recovery, may be a bridge that delays entry into the atmosphere, but the carbon dioxide would need to stay underground a very long time to really keep it out of the atmosphere and count as sequestration. The other downsides of carbon capture, even for gasification, are that it consumes significant additional energy and adds a significant extra cost.

In the early 2000's the notion was advanced of using UCG cavities for sequestering captured carbon dioxide from UCG-produced gas. While in theory the consumed coal seam volume could hold a fraction of its ultimate carbon dioxide product, this is an impractical idea for several reasons, at least in the foreseeable future. Carbon dioxide sequestration requires depths greater than a kilometer, and UCG

development is a long way from being able to do that with reliable and economic success. Both sequestration and UCG are challenging technologies that are early in their development towards mature confident industrial practice. Combining them squares their probability of success, roughly adding their probabilities of failure. Finally, and most fatally, sequestration absolutely requires an excellent if not perfect geological seal between it and the surface. UCG's wells introduce possible leak pathways. Large scale UCG operations, like large scale longwall mines, will tend to create rubble and fracture and tension zones in the rock that extend a long way above the coal seam – anathema to a sequestration site.

Methane comprises a significant fraction of UCG product gas. Methane is a much more potent greenhouse gas than carbon dioxide. Leaks of methane-containing product gas that eventually find their way to the atmosphere will add more warming potential than their carbon dioxide content would suggest. Even if entirely contained in the product stream, methane can not easily be water-gas shifted to separable carbon dioxide and when burned will have the same footprint as natural gas.

Surface gasification occurs in leak-tight vessels. UCG occurs in the open underground system. In small scale field tests to date, gas losses on the order of 5-20% have been common, even after awareness led to efforts to minimize it. Further development and a combination of using only low-permeability sites and keeping the vertical height of roof collapse and fracturing small would be expected to reduce gas leakage. Larger scale operations will make perfect gas containment more difficult.

As with other coal energy technologies, UCG will produce more greenhouse gases per unit of useful energy than many other energy sources. Coupling it with efficient carbon capture and sequestration could reduce this footprint to something approaching the footprint of natural gas energy without sequestration. Doing so at large scale will be a matter of economics and incentives, together with development and maturation of CCS technology and gas-loss-free UCG operations.

## 9 Summary of accomplishments and challenges

### 9.1 High-level process development accomplishments

At the highest level, relating to the goal of developing UCG into a mature, large-scale industrial process, U.S. efforts have:

- Demonstrated unequivocally the technical feasibility of UCG by a variety of methods in single modules at scales up to 10,000 Mg, using air or oxygen-steam firing in fairly thick seams of non-swelling coals to depths of 200 meters
- Demonstrated methods and technologies that are expected to be amenable to large scale operations, and developed experience, understanding, and models to assist with this scale up
- Created designs, project plans, and cost estimates for intermediate-scale demonstration plants and industrial-scale production plants
- Experienced, through RM1 in 1988, enough various hardware failures, operational difficulties, and surprises to be reminded that UCG was still early on the development path towards industrial maturity

- Demonstrated that the hazard of groundwater contamination from UCG operations is real, practices can affect the magnitude and spatial extent, and it will take great care and commitment to reduce the risk to an acceptable level.
- Documented most of the work very thoroughly for public use in enumerable reports.

## 9.2 Field test accomplishments

In field test scope, U.S. efforts have:

- Performed successful field tests in lignite, sub-bituminous, and non-swelling bituminous coal seams.
- Tried UCG once in a swelling bituminous coal seam, with severe operational challenges blamed on coal swelling and tar condensation
- Performed most of the field tests in seams that were relatively flat, shallow (40-150m), and moderately thick seams (6-8 m)
- Successfully performed a field test in a 30-meter thick subbituminous seam with good results (Rocky Hill), and successfully operated a field test in a 2.2-meter lignite seam, producing gas of poor quality (Tennessee Colony)
- Successfully performed a field test at a depth of 200 meters (Rocky Hill) and unsuccessfully operated a field test at a depth of 270 meters (Pricetown, but the depth was not the problem)
- Used air injection to produce from subbituminous and bituminous coals a gas with heating value between 4.3 and 7.4 MJ/Nm<sup>3</sup> (Hanna I and many subsequent tests). (3.0 MJ/Nm<sup>3</sup> from a thin lignite seam)
- Used oxygen-steam injection to produce from subbituminous and bituminous coals a gas with heating value between 8.4 and 12.5 MJ/Nm<sup>3</sup> (Hoe Creek II and many subsequent tests). (8.6 MJ/Nm<sup>3</sup> from a thin lignite seam). The efficiency parameters of the CRIP module of RM1 were comparable to those of surface gasifiers.

## 9.3 Technology accomplishments

In field test work, technology accomplishments in the U.S. have:

- Successfully ignited all field tests using a variety of methods. This often took multiple tries.
- Demonstrated repeatedly that given ignition at the injection well and a low-resistance flow link to a production well that the main phase of gas-producing operations, forward burn, is robust – it may be turned down or even stopped for hours or months, and it responds in a stable and predictable manner to changes in pressure, injection composition, and events such as roof collapse or sudden moving of the injection point
- Established and operated forward burn operations from a module that had been prepared/linked using each of the following methods/configurations. All but the first of these allowed acceptable forward burn operations.

- Used, with unacceptably high flow resistance and plugging, sand-propped hydraulic fracturing to link multiple vertical wells (Hanna 1 initial phase)
- Used reverse burns, with and without hydraulic fracturing, to link multiple vertical wells (Hanna 1 and many others)
- Used explosive fracturing to create rubblized coal between injection and production wells (Hoe Creek I)
- Used directional drilling of horizontal boreholes to link multiple vertical injection wells (the Extended Linked Wells (ELW) method; HC-III & RM1)
- Used a reverse burn to connect directionally-drilled injection and production wells completed into a steeply dipping seam (Rawlins I and II-2)
- Used directional drilling of an in-seam borehole in a steeply dipping seam to link this production well with an injection well completed lower in the seam (Rawlins II-1)
- Invented the CRIP technique to maintain the injection point low in the seam and repeatedly move it into or closer to new coal
- Used “Linear CRIP” to produce gas from a vertical well at the far downstream end of the CRIP injection well (Centralia SBK1 and the initial phases of Centralia PSC and RM1-CRIP)
- Used “Parallel CRIP” to produce gas from a horizontal borehole/well located in the seam some distance to the side of the injection well (Centralia PSC and RM1-CRIP)
- Used both short reverse burns and water jets to make short connective links between drilled boreholes and wells that had narrowly missed each other
- Successfully overcame the challenges of operating field tests in severe Wyoming winter weather
- Successfully moved the injection point and location of forward burn to different positions within modules of all the types above that are amenable to this
- Developed and applied methods for monitoring cavity- and burn-front development in real time
- Made improvements in the methods and extent of groundwater characterization before and after field tests
- Demonstrated at multiple sites that UCG can produce unacceptable levels and spatial extents of groundwater contamination.
- Demonstrated that UCG contamination can be difficult and expensive to remediate.
- Characterized the groundwater quality contamination, characterized and remediated sites, and made progress in understanding the mechanisms involved and possible scenarios, and approaches to minimize it
- Developed and tested the “Clean Cavern” approach to terminating a UCG module/cavity in a way that minimizes groundwater contamination

- Came to understand that while gasification of steeply-dipping beds may be thermally more efficient than horizontal seams, they are much more prone to escape of product gas towards the surface with its associated transport of contaminants and industrial hygiene issues.
- Came to understand that while gasification of very thick seams may be thermally more efficient than thin or moderately-thick seams, they will be more difficult for balancing the trade-off between too much inward water permeation at the bottom and the escape of product gas and contaminants at the top. They also pose a greater mining-engineering challenge for managing the upward extent of overburden collapse and fracturing, which is tied to upward gas escape and contaminant transport.

#### 9.4 Field test challenges

In field test work, U.S. technology challenges have included:

- It often took multiple tries and modifications to achieve ignition, including as late as RM1.
- The high air pressures of reverse-burn linking, including its associated air-acceptance testing) sometimes mechanically damaged injection and instrument wells (RM1, Pricetown) and sometimes created unwanted permeability and communication channels (RM1, Hanna cross-talk issues)
- The high air pressures used for reverse-burn linking pushed product gas far out into the formation (directly observed in the heavily-monitored RM1 and likely occurred in other reverse-burn linked tests). This is a mechanism for contaminant transport
- The high air pressures used for reverse-burn linking and its associated air acceptance testing could create undesirable permeability where it was not wanted, including near the top of the coal seam (RM1, Rocky Hill, probably others)
- When directionally drilled process boreholes and wells did not intersect as planned, they must be connected. Water-jetting can connect short distances, but short reverse burns made it possible to connect distances more than a meter. These add inconvenience and the pressure disadvantages noted above
- In a swelling bituminous coal, reverse burn links had insufficient permeability for forward-burn operation, and even after various burns that opened up permeable pathways, they did not stay open
- Thermal and/or mechanical damage to wells was not uncommon. High temperatures sometimes melted well liners/casing in unintended places. Mechanical stresses from roof collapse events, overburden strains, and thermal stresses ruptured or cracked wells and/or their surrounding cementing, including injection, production, and instrument wells. High injection pressures from air acceptance testing and reverse burn operations sometimes damaged wells.
- Injection points were sometimes plugged by mineral slag produced by the high-temperatures of oxygen-steam injection

- The above well failures sometimes caused injection to occur in unintended places and production gas to escape from unintended places.
- High particulate production and erosion of piping from it was a problem in several field tests. Particulate loadings correlated with gas velocity but fluctuated according to factors not well understood.
- Many mundane operating and equipment problems occurred. These were of a nature that is common with technologies that are early in the development stage and lack a mature set of engineering practices, equipment, and cadre of experienced operators. A high degree of watchfulness and creative ingenuity were needed for most field tests.

## 9.5 Scientific understanding accomplishments

In terms of understanding the process scientifically, work in the U.S. has:

- Demonstrated repeatedly that for a given coal the product gas quality is largely determined by an energy balance, with the two main losses being heat used to dry and heat roof rock, including its in-falling rubble, and to vaporize in-flowing water. Strong, spalling-resistant roof rock and low coal and rock permeabilities are desirable.
- Demonstrated repeatedly that the highest quality gas is produced when the injection point is low in the seam, the burn is low in the seam and the injection point is surrounded by coal and char and their rubble, and there is little involvement of roof rock.
- Demonstrated repeatedly that for a given formation permeability, lowering the cavity pressure causes more water to flow in, decreasing efficiency. Raising the cavity pressure is limited in the extent it can reduce influx, and it causes more gas to escape, reducing yield and transporting contaminants outward.
- Learned the shape and nature of UCG cavities by real-time monitoring, drill-backs, and full excavation (as tall or taller than wide, growing toward the production well twice as fast as backwards, and largely filled with ash, char, coal, and overburden rubble)
- Learned the shape and nature of link paths by the same methods (upwards V-shaped, and filled with char (if reverse-burned) and rubblized char and dried coal)
- Arrived at an improved conceptual model of UCG and scientific understanding of the phenomena involved
- Developed improved methods for making more accurate material balances around the process by using a nitrogen balance and tracers
- Developed a suite of simple models for screening complicated coal fields, estimating product gas composition, and estimating industrial-scale mass and energy balances and cost estimates (LLNL's UCG-ZEE, EQSC, and UCG-MEEE)
- Developed two integrated, multi-physics UCG process simulators that predict the time history of cavity growth, product-gas composition, and surrounding temperatures and pressures (LLNL's 2-D CAVSIM and 3-D UCG-SIM3D)
- Repeatedly concluded that site selection is extremely important for UCG success in terms of technical performance and efficiency, and environmental cleanliness

## 9.6 Environmental understanding and accomplishments

In terms of UCG's environmental impacts, work in the U.S. has:

- Concluded that for UCG to mitigate coal's high greenhouse gas footprint: it can not divert energy production from low-footprint sources to coal; it must incur the added costs of carbon capture and sequestration; sequestration technology must be demonstrated and accepted; it is very unlikely to use its own cavity for sequestration volume; and fugitive losses of methane-containing product gas must be eliminated
- Concluded that causes of unacceptable groundwater contamination included fracturing of the overburden, high injection pressures, well-completion flaws, and/or operating near groundwaters that are valued
- Developed a general understanding of the mechanisms and scenarios of groundwater contamination, with the escape of contaminant-carrying gas being both the main vector to carry contamination far
- Identified approaches to better assure that groundwater contaminating conditions are detected early so they can be remedied
- Identified approaches to minimize groundwater contamination and its impacts.

## 10 Concluding remarks

Recent U.S. work between 2005 and 2014 improved understanding of UCG's environmental aspects, produced improved models, matured site selection processes, and contributed to the review and sharing of UCG information. But the main program of the 1970's and 1980's is when the big contributions were made.

The United States work of the 1970's and 1980's produced great advances in UCG understanding and technical accomplishments. The technical feasibility of UCG was demonstrated convincingly in the western world. It showed that UCG operations could be designed, constructed, started, operated, and shut down safely. The U.S. started with reports from the Soviet Union that described UCG operations and phenomena, making use of Soviet methods during many field tests. Multiple organizations working at different sites developed a breadth and depth of competence and understanding of UCG, and used this expertise to experiment, innovate, and make great advancements in UCG capabilities, and technology.

Air was injected to make low heating value gas (4-7 MJ/Nm<sup>3</sup>), and mixtures of oxygen and steam were injected to make medium heating value gas (8-13 MJ/Nm<sup>3</sup>). U.S. field test operations were at the scale of 1,000 to 10,000 tons of coal in a single module, although some of the modules had multiple burn cavities in them.

Operations almost always ended up working, but they did not always go smoothly as planned. Hardware issues and challenges in the underground and extremely hot environment were a frequent reminder that UCG is still low on the technological development curve towards mature industrial practice.

Some field tests resulted in groundwater contamination. This led to a much greater awareness and understanding of this problem, and recommended approaches to minimize it. The final Rocky Mountain 1 test used many of these and contamination was minor, local, and reduced to deminimus levels after a

period of pumping. It remains to be seen if subsequent UCG operations, especially ones at scale can be operated with acceptably low environmental impacts.

Technologies were developed, making use of the rapidly improving technology of directional or horizontal drilling and well completions. These showed promise for scale-up to larger and deeper operations while retaining process efficiency and control. ELW had first been tried in a successful improvisation at Hoe Creek III, and then fielded at Rocky Mountain 1. The greatest technological advance was the invention of the CRIP technique. After successful demonstration in the Centralia field test, CRIP was fielded and performed excellently at the Rocky Mountain 1 test. Designs based on CRIP show great promise for cost-effective scale-up to large, deep and efficient operations.

Most of the early large-scale designs and plans naively assumed that large industrial scale operations would be scaled up with a simple pilot program to gather values for a few key parameters. The complexity and difficulty of UCG was such that despite a long well-funded program, the final field test, while deploying many technical and environmental advances, was not much more than twice the size of the first field test, 14 years earlier. There were no long-term operations of multiple modules or the execution of a full “mine plan.” This was not for lack of interest or enthusiasm for industrial scale – scale-up to a size that would help U.S. energy security was always on researchers minds and addressed in nearly every report.

Doing UCG well, smoothly, and with low environmental impact was simply difficult and required experience and improved methods that needed to be invented and practiced. Much of the test design, construction, and operations were being tried for the first or second time by people doing these things for the first or second time. They faced the challenges always posed by geology, thermal processing of coal, and process engineering pilot start-ups, often in remote locations in harsh weather.

This was a period of strong and continued investment, intense activity, and a great pace of development and learning. Some of the keys to its technical success were long-term continuity of funding and the institutions working on it, sharing of results in public conferences and reports, and determination to understand UCG and make improvements.

While the many field tests formed the centerpiece of the program, they were not isolated activities. The program was robust and well rounded. Measurements of gas composition and quality were made to understand and improve the process, not to advertise success. There was iteration between field test observations, scientific understanding of phenomena, modeling, and lab experiments, with each informing and improving the other. Field tests were first and foremost experimental trials and innovation test-beds. They were not marketing endeavors designed to attract investors and project partners. They emphasized learning, understanding, and technical advancement over simple metrics such as tons gasified. Field tests were highly instrumented and monitored, and drill-backs were common. The mechanisms and geometries of cavity growth, and the contents and nature of the cavities became understood. Conceptual models of the process evolved to better explain and predict observed phenomena.

Program participation was well-rounded. Government research institutions led much of the field test and modeling work. Large energy companies and small UCG-niche companies also had programs that typically included field tests, sometimes with government support and sometimes not. University researchers were involved with laboratory experiments and model development. Experience, capabilities, and knowledge and insight were gained by those actively involved. A sizeable cadre of competent researchers, engineers, and technicians by the 1980’s made the potential growth of an industry feasible. This has now been lost, as all but the most junior of participants of that generation are past retirement age.

Their legacy of reports, and reviews such as this one can convey only a fraction of what these workers knew.

The Annual UCG Symposia tied all these efforts together, fostering communication among researchers to build upon each other. Organized by the DOE, participation and written papers were expected of DOE-funded projects, but many others attended and presented. Because of government funding, a large fraction of the activities was documented well in publicly accessible reports.

UCG understanding and technology advanced in the U.S. in a crucible that mixed creative ideas and the hard realities of field test operations. Observations and results, surprises and disappointments, revisions to mental and mathematical models, and the desire to understand and innovate moved the researchers toward better ways of doing UCG.

A consensus developed in the U.S. that UCG's future would be in deep horizontal seams of moderate to large thickness, ideally with low-permeability coal and surrounding strata, and a strong overburden. Directional drilling and CRIP appeared best for process control, efficiency and economics. Further testing and development would be needed to assure its reliability, sort out a preference for its linear or parallel embodiment, optimize it, and/or innovate to something even better.

The U.S. UCG program of the 1970's and 1980's was extraordinarily productive and successful at advancing a difficult technology. It began with very little domestic knowledge or experience. It ended with a large cadre of experts, successful single-module field tests, a good understanding of the phenomena involved, predictive models, new and more efficient technology and methods, and a good understanding and plans of what next steps were needed to scale up and mature to large-scale industrial operations.

## 11 Acknowledgements

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## 12 References

### 12.1 Sources

Most UCG literature is in the form of topical reports, and papers in conference proceedings. The following suggestions may make it easier to find and acquire references.

Reports by government organizations, reports on government-funded work, and conference proceedings organized by government organizations that have been approved for public release may be obtained from the U.S. Department of Commerce's National Technical Information Service (NTIS, <https://ntrli.ntis.gov/NTRL/>) and/or (for documents funded or authored by DOE or its institutions) DOE's Office of Scientific and Technical Information (OSTI, <https://www.osti.gov/scitech/>). These are the first places to look, as they should have whatever LLNL and NETL have.

If not available from NTIS or OSTI, LLNL's library in Livermore, CA (<https://library-ext.llnl.gov/>) may have a copy of LLL/LLNL reports that have been approved for public release.

If not available from NTIS or OSTI, NETL's (METC's successor) library in Morgantown, WV (<https://www.netl.doe.gov/library>) may have a copy of MERC/METC reports, their organized conference proceedings (including the Annual UCG Symposia), and ERDA/DOE reports.

Older LERC/LETC/WRI reports do not appear to be easily available through the library of its successor institution, WRI.

IEA Clean Coal Centre reports may be purchased from: <http://www.iea-coal.org.uk/site/2010/home> (Publications), and most individual papers/presentations from their Workshops may be found at the same site: *click* CONFERENCES / UNDERGROUND COAL GASIFICATION / Workshop / Enter Conf. System / Conf. Prog.

Proceedings of the Pittsburgh International Coal Conference are available for purchase from the conference coordinators (<http://www.engineering.pitt.edu/pcc/>)

Proceedings from conferences, workshops, and courses organized by the UCG Association/Partnership (now closed) were available to paid members and attendees. It is unknown if a repository remains.

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