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UCID- 21853

Lawrence Livermore National Laboratory Underground Coal Gasification Project: Final Report

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October 15, 1989

Lawrence Livermore National Laboratory

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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LAWRENCE LIVERMORE NATIONAL LABORATORY UNDERGROUND COAL GASIFICATION PROJECT: FINAL REPORT

C.B. Thorsness and J.A. Britten

ABSTRACT

The Lawrence Livermore National Laboratory (LLNL) has been actively developing Underground Coal Gasification (UCG) technology for 15 years. During these years the goal of the project has been to develop a fundamental technological understanding of UCG and foster the commercialization of the process. In striving to achieve this goal the LLNL project has carried out laboratory experiments, developed mathematical models, actively participated in technology transfer programs, and conducted field test experiments. As a result of this work the Controlled Retracting Injection Point (CRIP) concept was developed which helps insure optimum performance of an underground gasifier in a flat seam, and provides a means to produce multiple gasification cavities. The LLNL field work culminated in the Rocky Mountain I field test in which a gasifier using the CRIP technology generated gas of a quality equal to that of surface gasifiers. This last test and others preceding it have demonstrated beyond any reasonable doubt, that UCG is technically feasible in moderately thick coal seams at modest depths. However, to fully assess the potential of UCG, more work is required to determine the technical feasibility of gasifying deep, thick and/or swelling coal seams.

INTRODUCTION

Underground coal gasification is a process which has the potential to turn coal resources into useful gas products without the need for mining. Cost projections (Gash et al., 1983) have indicated that UCG may be cheaper than surface gasification as a result of the lower capital and raw material costs. This stems from the fact that the no reactor is needed, since the underground system serves this purpose, and that unmined coal is far cheaper than mined coal. In addition UCG has the potential of greatly expanding U.S. coal reserves since it has the potential to extract energy from otherwise unminable coal deposits.

The Underground Coal Gasification Project at the Lawrence Livermore National Laboratory was first funded in fiscal year 1974. Funding for the project has been provided primarily by the Department of Energy and its predecessors with some occasional support from others, most notably the Gas Research Institute. The goal of the project was to advance UCG technology along many fronts toward its eventual commercial application. Efforts have included: fundamental theoretical and experimental investigations of the complex thermochemical and physical processes associated with in situ combustion and gasification; design and engineering of equipment and processes crucial to initiation, maintenance and analysis of UCG field tests; execution of field tests; technology transfer and consultation with organizations, both domestic and foreign, regarding design and operation of field tests; and maintenance and expansion of a global UCG data base.

From this perspective in time the major accomplishments of the LLNL UCG project have been:

- Pioneering the use of steam/oxygen gasification and directionally drilled links
- Developing the Controlled Retracting Injecting Point (CRIP) technology
- Developing a state-of-the-art UCG model
- Carrying out 7 field tests

The use of steam/oxygen, instead of air, as the injected gasification agent in UCG was an important step in UCG development since it is a prerequisite for producing a gas which can be upgraded to easily transportable products such as methane and methanol. The development of the CRIP method (described later) of gasification demonstrated a positive means of control of the development of the underground reactor system. Our efforts on modeling resulted in the production of the CAVSIM computer code which we believe captures the essential physics of gasification of non-swelling coal seams at modest depths. Finally, the progress of the project and the development of UCG technology is probably best represented by the progression of the seven field tests we performed or participated in. Details of these accomplishments and other related work have been well documented in numerous project reports.

As it is not the intent of this report to summarize all the work performed by the project, the interested reader is referred to the Appendix for a list of all reports issued by the project. This report provides a brief overview of the progress of the project by focusing on the seven field tests performed by the project, followed by a discussion of our perception of the state of current UCG technology.

FIELD TESTS

The seven field tests performed or participated in by LLNL are listed in Table 1. All but the first of these include actual gasification of coal. The first six field tests were done under the direct control of LLNL. During the course of these field tests several concepts of UCG were explored, including three distinct well linking techniques: explosive fracturing, reverse combustion, and directional drilling.

Table 1. Field Tests

Test	Where	When	Coal (Tons)	Gas (Btu/scf)	Comment
Kemmerer	Wyo.	1974	—	—	Explosive fracturing test
Hoe Creek I	Wyo.	1976	123	100	Air/explosive fractured
Hoe Creek II	Wyo.	1977	1200	105	Air/1st oxygen use
Hoe Creek III	Wyo.	1979	3250	210	Oxygen/direct. drill
LBK	Wash.	1981	140	270	CRIP developed
PSC	Wash.	1983	2000	250	CRIP demonstrated
RM I	Wyo.	1988	10000	290	CRIP proved

The first field test, the Kemmerer experiment, was conducted at the Kemmerer mine in western Wyoming. This test explored the feasibility of using explosive fracturing as a means of permeability enhancement of the seam, a prerequisite for successful gasification. A small explosive charge was placed in a shallow hole drilled in coal and detonated. Various measurements of blast effects were made. This test was performed to help direct explosive fracturing modeling and prepare for a larger test at a site near Gillette, Wyoming.

After the Kemmerer test, the Hoe Creek series of gasification tests were performed at a site near Gillette, Wyoming in the Powder River Basin. The Hoe creek site was chosen for a combination of practical and technical reasons. One practical consideration for a federally funded project was that the site was on federal land under control of the Bureau of Land Management. Technical considerations included the fact that the site was typical of the entire Powder River Basin, with a 100 ft. thick coal seam at a depth of about 1000 ft. To reduce drilling cost of the initial experiment, a burn in shallower coal about 150 feet deep, located at the same site, was chosen.

As it turned out all three tests at the site were done at this shallow depth. Two seams were present at this location, the Felix 1 and 2 seams. The Felix 2 seam, the

primary target, was a 25 ft. thick subbituminous seam. Above this was the Felix 1 seam of similar composition with an average thickness of about 15 ft. The seams were separated by 15 to 30 ft. of clayey siltstone.

The Hoe Creek I test used explosive fracturing to link two process wells separated by 33 ft. Only 123 tons of coal were gasified during the 11 days of active air gasification. Thermal instrumentation and post-burn analysis indicated that the explosives had increased permeability primarily at the top of Felix 2 seam. This resulted in active gasification occurring only near the top of the seam and thus the product gas was of marginal quality. Based on the results of this test explosive fracturing was abandoned as a linking/preparation step for UCG.

The second test at the same site, Hoe Creek II, used reverse combustion to link the two primary process wells located 60 ft. apart. This was primarily an air gasification test. However a short test, 2 days, of steam/oxygen injection was performed. The forward gasification phase lasted nearly 60 days and 1200 tons of coal were gasified yielding an average heating value of 105 Btu/scf. This test demonstrated that placement of the injection point was a key factor in determining the performance of a UCG process.

After only five days of operation of the Hoe Creek II test, the produced gas quality began to sharply decline until it eventually approached zero. Various combinations of flow rates and pressures were tried in an unsuccessful attempt to reverse the trend. Production through a secondary production well located 15 ft. away from the primary one, was tried to no avail. It was suspected, and later confirmed, that the cause of the problem was the destruction of the injection well such that air was being injected at the top of the seam rather than the bottom as originally constructed. To confirm this, and to allow continued operation injection was switched to a 2 in. tube that ran to the bottom of the injection well intended originally as a dewatering line. The gas quality recovery following this operation was dramatic. Within an hour, gas of over 100 Btu/scf was being produced. Operation during the remainder of the test used this tube, which remained intact throughout the test. After the successful short term oxygen/steam test, air gasification continued with a gradual decline in gas quality as the burn cavity grew.

Post burn coring indicated that both seams Felix 1 and 2 had been gasified. The cavity walls in the lower Felix 2 seam were relatively vertical. The clear lesson of the Hoe Creek II experiment was that the primary control to be exercised over a UCG process is accomplished through location of the injection point. While other process changes seem to have little influence on the course of the gasification, the placement of the injection point at the bottom of the seam resulted in significantly improved performance.

During reverse burn linking of the Hoe Creek II process wells, thermal instrumentation indicated that a number of reverse burn channels had moved away from the injection well. One of these paths appeared to be located at the top of the Felix 2 seam. The instrumentation was not adequate to determine which channel actually reached the production well and thus formed the primary path for the flow of gases during forward gasification, but indications were that it could have well been this channel located high in the seam. It was unclear if this initial geometry had led to the early problems with the injection well and the loss of gas quality. In addition, UCG experiments at Hanna, Wyoming which had initially yielded extremely good results with air gasification in a reverse burn linked system, experienced severe linking problems during the Hanna IV field experiment. It appeared that directional drilling of a link to provide the initial connection between injection and production wells may be an attractive alternative to reverse burn linking, since it would be possible to achieve close control of placement. Because of these factors, and because of a desire to remove uncertainty about the contribution of initial link geometry to the forward gasification performance, it was decided to use a directionally drilled link during a third test at the Hoe Creek site.

The Hoe Creek III test used directional drilling to link vertical injection and production wells located 100 ft. apart. The Hoe Creek II experience showed the importance of maintaining a bottom seam injection point. Consequently the drilled link was placed close to the bottom of the seam and the vertical injection well was redesigned to try to insure its survival. This included placing a large diameter pipe inside the injection well casing to provide additional protection for the 2 in. injection lance.

The Hoe Creek III test was primarily a steam/oxygen test. Gasification for more than 50 days resulted in the gasification of 3250 tons of coal from the Felix 2 and Felix 1 coal seams, with the bulk of the coal being removed from the upper Felix 1 seam. The average gas heating value was 210 Btu/scf, considerably below that which was anticipated. The improvement over the Hoe Creek II test in heating value was entirely a result of the use of steam/oxygen and not a result of better performance. The large involvement of the Felix 1 seam resulted from the partial destruction of the injection well.

The Hoe Creek III test demonstrated that it is very difficult for a vertical injection well to survive in the harsh underground environment. In addition it was found that the initial link placed at the bottom of the seam rapidly evolved into steep sided "V" growing rapidly to the top of the seam. It was thus concluded that initial link placement was not a key element to successful gasification because of its rapid growth and movement of gas flow to the top of the seam. It also became clear that that the Hoe Creek site 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

influx. Also 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.

Based on the experience of the Hoe Creek experiments two things were done. First, a new, more favorable site was sought. The characteristics deemed of primary importance were low coal and overburden permeabilities. In addition a coal with a drier and more competent overburden was sought. Secondly, a new method of performing the gasification process, the CRIP process, was conceived.

The CRIP process was devised as a means to insure that the reactant injection point in a seam would remain near the bottom where it was originally placed. Low seam injection placement has two desirable effects. It delays the interaction of the developing burn cavity and the overburden for as long as possible. Heating and drying of inert overburden material reduces the amount of energy available for useful gasification reactions, and the result is a lowering of the quality of the produced gas. The bottom seam placement also means that the injected reactants must permeate through a developing ash pile. This allows the ash rubble to help direct the reactants toward the cavity walls where fresh coal is available for gasification. It also avoids the situation in which reactants are injected in a void space above the rubble filled cavity. In this later geometry ash and inert roof rubble can effectively prevent gasification of fresh coal underneath.

In the CRIP concept, the injection point is maintained at the bottom of the seam by adopting the use of a horizontally drilled link well as the injection well. The horizontal well is lined with a stainless steel tube through which steam and oxygen are introduced to the seam. This horizontal injection well is placed along the bottom of the seam in the active gasification area and as a result any destruction of the injection tubing still leaves the injection point at the bottom of the seam. In addition to providing a means of guaranteeing a bottom seam injection point, the CRIP concept allows more than one gasification cavity to be generated from a single horizontal injection well. This is accomplished by inserting a movable igniter/torch assembly inside the injection tubing. The torch can be ignited remotely and and allows the injection tubing to be cut at a desired location. Thus when the initial gasification cavity at the end of injection tube reaches the end of its useful life the igniter/torch assembly can be positioned at a point upstream from the cavity, the injection tubing cut, and a new gasification cavity developed. This process then can be repeated as required.

The CRIP geometry was first field-tested as series of small scale tests performed at the Widco mine site in Centralia, Washington. The Widco site was chosen for two primary reasons. The coal appeared to have the characteristics we were looking for and the mine operators allowed us to carry out small scale tests at an exposed coal face

which would allow subsequent excavation. In total, a series of five gasifications were performed during what is called the Large Block (LBK) experiment. Each test used a separate horizontal drilled link, lasted 3 to five days, and consumed about 20 tons of coal. In all tests a newly developed silane/propane igniter system was used to initiate the gasification. During the five tests various flow rate schedules were followed. These included the use of various steam/oxygen ratios as well as an air gasification test. In one of the tests a second burn was initiated in which the injection liner was burned through with the igniter/torch assembly and a second cavity was developed. This was the first test of the CRIP process.

After completion of the gasification phase of the LBK tests the small cavities were excavated. This 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 be mostly filled with rubble and thermally altered coal. This excavation gave us the first indication that the ash left after complete consumption of the coal might play a key role in distributing injected reactants in a developing UCG cavity.

Following the LBK tests came the Partial Seam CRIP (PSC) field test. This test, like the LBK tests, was conducted at the Widco mine. In fact, the location of experiment was in close proximity to the previous LBK test. The test was conducted at the high wall left after mining and excavation operations had removed the coal which contained the LBK tests. Unlike the LBK tests the PSC test was a full scale operation. It used the top part (roughly 20 ft.) of the Big Dirty seam located approximately 900 ft down dip from the exposed high wall and approximately 200 ft from the ground surface.

The PSC test was the first full scale test of the CRIP concept. During the operation of the 30 day steam/oxygen gasification 2000 tons of coal were gasified yielding an average gas heating value of 250 Btu/scf. Two cavities were developed. The first was initiated at the end of the horizontal injection well with production primarily through a vertical production well. The second cavity was initiated through the use of the CRIP process (cutting through the injection well liner). During the second cavity gasification production was through a horizontal production well.

The PSC test demonstrated that the CRIP process was technically feasible on a full scale system. It also indicated that the desired increase on product quality could be effected by initiation of a new cavity. However, operational and other difficulties somewhat clouded the issue as to the exact effectiveness of the CRIP operation. These factors included frequent steam boiler failures, the limited length between the first and second cavities which resulted from geometry constraints caused by process well drilling problems, and the delayed use of the horizontal production well caused by failure of the cavity to link with it early in the process.

A unique opportunity presented itself after the completion of the PSC test. The mine operators began to actively mine coal in the area of the test. As a result we were able to excavate the outflow channel and burn cavities. This open cavity presented an excellent picture of the nature of the underground system at the end of a large gasification process. The excavation revealed a V-shaped outflow channel filled with char very similar to what we inferred to happen to the drilled channel in the early phases of the Hoe Creek III test. 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. The results of the excavation were very similar in aspect to what our modeling effort had predicted. The excavation reinforced our idea that ash and overburden rubble play a key role in directing the injected oxygen and steam to the walls where fresh coal is available. The model indicated that the performance of a mature gasification process is determined by the relative amount of oxygen reaching the wall versus that which flows upward into the cavity void region to recombust product gas. The excavation results were consistent with this view.

The encouraging results of the PSC test and its indication of the viability of the CRIP technology led to plans for a larger scale test at the Widco site. Because of money constraints the plans evolved into a joint DOE and Gas Research Institute funded effort which would include participation by LLNL, the Western Research Institute, Energy International, and Stearns Roger Engineering Company. Unlike previous tests in which LLNL had total control of design and operation, our role in the next test would be to coordinate our efforts with the other participants. Stearns Roger Engineering acted as the prime contractor for the overall test.

Because of difficulties in establishing a working relationship with the Widco mine operators the test location was shifted from the state of Washington to Wyoming. The test was renamed the Rocky Mountain (RM) I test and initial drilling and site construction began in the spring of 1986. The location for the test was near Hanna, Wyoming very near the Hanna series of UCG test done in the 1970's by the DOE. The target coal was a non-swelling high volatile C bituminous coal with an effective thickness for gasification of 25 ft. located at a depth of approximately 350 ft. Unlike the coal at earlier Hanna test sites, the seam at the location chosen for the test exhibited considerably more permeability (averaging over 100 milliDarcies) and as a result problems of water intrusion and gas loses were a concern.

The RM I test consisted of two separate modules, the Extended Linked Well (ELW) module and the CRIP module. The two modules were designed to be run independently but concurrently. Both modules used horizontal production wells. In the ELW module the horizontal production well was intersected with two vertical injec-

tion wells. In the CRIP module the horizontal production module was intersected near its end with a horizontal injection well which had a stainless steal liner and an igniter/torch assembly for use in the CRIP process. The test was intended to determine the difference in performance of LLNL CRIP technology and the ELW vertical injection well technology in a common seam, and to allow long term operation to demonstrate the reliability of UCG operations.

The active phase of gasification of the RM I lasted the planned 100 days and over 15,000 tons of coal were gasified. The ELW module had to be shut down early after gasifying 4100 tons of coal during approximately 50 days of operation. Shut down was necessitated by the arrival of small amounts of oxygen at the production well. The CRIP module operated for the entre 100 day period and gasified 10,000 tons of coal. The CRIP module operation included the generation of 4 separate cavities. During the experiment, three CRIP maneuvers (i.e. the operation of cutting through the liner and starting a new cavity) were performed.

Both modules produced a good heating value gas. The CRIP module averaged about 290 Btu/scf and the ELW module 260 Btu/scf. However the CRIP module was considerably more efficient than the ELW module. One key efficiency parameter relating product value to cost is the ratio of product heating value to injected oxygen. This parameter was 50% higher for the CRIP module than the ELW, and exceeded that of any previously conducted UCG test in flat lying coal.

The superior performance of the CRIP module with respect to both coal gasified and efficiency is directly traceable to the difference in geometry between the two modules. The low injection point and new cavity generation ability inherent in the CRIP technology leads to optimum performance in a given setting. The vertical injection well geometry used in the ELW geometry 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 proportionally large amount of overburden. The CRIP module on the other hand began gasification from the bottom of the seam and only involved the overburden as the cavity grew in size. Also, recovery of product gas quality was clearly demonstrated following the CRIP maneuvers. Increases of as much as a factor of two were seen after initiation of a new cavity.

The active forward gasification phase of the RM I test demonstrated:

- The importance of a bottom seam injection point
- A proof-of-principle of the CRIP process
- A gas quality equal to surface processes

This later point is demonstrated by examining Table 2 where results of the RMI test are compared to results from surface gasifiers. The last parameter E_L is an efficiency parameter used by surface gasifier researchers which is basically a measure of the cost of the injected steam and oxygen to the heating value of the produced gas. Thus lower numbers correspond to more cost effective operation. By examining the table it is clear that the CRIP module of the RM I test performed as well as the average surface gasifier.

Table 2. Comparison of UCG with Surface Gasifiers[1]

Parameters	Lurgi dry ash	Shell	KRW	U-Gas	UCG RM I CRIP
Coal Type	Wyoming	Texas lignite	N. D. lignite	Wyoming	Wyoming
T, F	900	2530	1566	1300	539
p, psia	460	160	230	30	70
H2O/coal, mole/mole	1.74	-	0.31	0.65	0.23
O2/coal, mole/mole	0.23	0.45	0.37	0.29	0.27
Gas comp. (dry) CO	18.8	52.4	39.0	33.6	12.2
CO2	29.6	6.2	31.6	15.6	35.6
H2	38.8	28.8	24.2	36.6	39.5
CH4	11.9	0.1	4.2	3.8	9.5
E_L	1.64	1.43	1.73	1.44	1.6

[1] Surface gasifier data from Penner (1987).

CLOSURE

From our perspective of 15 years in the UCG research we feel the following issues have been answered:

Technical feasibility - The results of field tests run to date have unequivocally established the technical feasibility of UCG in coals at moderate to shallow depths using air or steam/oxygen as the gasification agent.

Cavity characteristics in mid-sized seams - Based on the modeling work and the excavation of field tests the general nature of cavities formed during gasification with a bottom seam injection point are understood. The cavities, to a first approximation, are symmetric with respect to the injection point, consist of rubble filled cavities, and have cavity walls which are nearly vertical. Away from the active cavities horizontal outflow channels starting as drilled holes in the seam tend to grow into a V-shape in cross-section.

Positive control method - The CRIP process appears to offer a method of positive control of the progress of gasification and provides a means to generate new cavities as needed.

On the other hand several issues remain unresolved:

Resource base - In order for the size of the resource base applicable to UCG to be quantified three things need to be resolved: the feasibility of gasifying deep seems (depths greater than 1500 ft.), the behavior of the gasification process as a function of seam thickness, and the behavior of swelling coals.

Behavior of the commercially most attractive seams - The commercially most attractive seams are the very thick seems (50 ft. or greater).

Nearly all the work to date has been done in roughly the same thickness seam (20-30 ft.) located at modest depths (shallower than 500 ft.). Although modeling work is a guide, we have no good experimental evidence to indicate the way in which performance varies as the seam thickness changes. Also it is possible that the mechanisms that appear to dominate performance in the shallower mid-thickness seams change drastically when deep coals or very thick seams are gasified.

The motivation to look at deep seams includes not only the issue of expansion of our coal resource base by demonstrating a means of extracting energy from umninable coals, but also the fact that as one goes deeper the coal and matrix rock permeabilities tend to decline and no useful aquifers are present. These factors may mean that deep coals might be very attractive from an environmental standpoint. Based on the limited work in Europe on deep coals their gasification clearly remains a formidable technical challenge.

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APPENDIX A

The following are LLNL Undergroumd Coal Gasification reports:

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UCRL-51595	The Stability of Flame Front Propagation in Porous Media with Special Application to In Situ Processing of Coal, D.W. Gregg	June 1974
UCRL-75990	The LLL In Situ Coal Gasification Program D.R. Stephens, et al. (3) J.D. Salisbury	August 1974
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UCRL-51835	Coal Plasticity and the Physics of Swelling as Related to In Situ Gasification, R.L. Wong	June 1975
UCRL-76984	Correlations Between Measurements and Calculations of High-Explosive-Induced Fracture in a Coal Outcrop, T.R. Butkovich	July 1975
UCRL-51904	In Situ Gasification of Softening Coal R.L. Wong	September 1975
UCRL-51909	High Explosive Fracturing Studies in Coal, J. R. Hearst and D. B. Larson	September 1975
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