UCRL- 92068
PREPRINT

CIRCULATION COPY
SUBJECT TO RECALL
IN TWO WEEKS

UNDERGROUND COAL GASIFICATION REVIEW

D. R. Stephens
R. W. Hill
I. Y. Borg

This paper was prepared for submittal to:
The 18th Annual Oil Shale Symposium and the
Western Synfuels Symposium, Grand Junction, CO,
April 24-26, 1985

Lawrence Livermore National Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

UNDERGROUND COAL GASIFICATION REVIEW*

D. R. Stephens, R. W. Hill, and I. Y. Borg
Lawrence Livermore National Laboratory
Livermore, CA 94550

ABSTRACT

Underground coal gasification appears to be one of the most attractive sources of feedstock to produce synfuels from coal because the process can produce methanol and substitute natural gas at prices competitive with existing energy sources. Savings in the form of reduced oil and gas imports from the first year of commercial operations would pay for the entire R&D budget necessary to perfect the underground coal gasification process.

The technical feasibility of underground coal gasification has been well established by 21 small scale field tests carried out in the U.S. since 1973. Cost estimates based on the resultant data are encouraging. Methanol is estimated to cost $0.52/gal (without tax) and SNG is estimated to cost $5.19/10^6$ Btu, all in 1982 dollars. The environmental effects associated with the technology appear to be acceptable. Successful commercialization of the process would probably triple the proven reserves of U.S. coal, which would be sufficient to last for hundreds of years.

At this stage of development, underground coal gasification is a high risk technology and will remain so until large scale field tests are successfully carried out. These tests are recommended by the Gas Research Institute and by the American Institute of Chemical Engineers. A seven year program costing about $200 million would permit initial commercial production in ten years.

A recent small scale field test, the Centralia Partial Seam CRIP test, was very successful. Steam and oxygen was employed to gasify 2000 tons of coal over a 30 day period, producing 250 Btu/scf gas. A larger scale test is presently being planned for Centralia, Washington, involving the U.S. DOE and an industrial consortium led by the Gas Research Institute.

This underground coal gasification review is based in part on a recent status report (Stephens et al, 1985). We thank the publishers of Mineral Processing and Technology Review for granting permission to reproduce portions of that article.

INTRODUCTION

In the decade or more that researchers at LLNL and other institutions have been developing the technology for underground coal gasification, public attitudes toward energy have oscillated from widespread complacency (1972) to near panic (1973, 1979) and back to complacency. Analysts today believe that the world has fossil-fuel reserves to last at least 100 years (Parent 1984; Edmonds and Reilly, 1983). While this may seem to justify the current complacency in the U.S. toward energy shortages in the near future, it says little about the adequacy of U.S. supplies. Further a 100 year supply does not guarantee timely development of those resources to minimize crises or guarantee a healthy U.S. and world economy.

Amongst energy analysts (who have a spotty record so far as prediction is concerned) there is a consensus on domestic energy consumption:

1. Although energy consumption will increase, per capita consumption will decline.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

2. Use of oil will increase somewhat by the year 2000. With a projected continued decline in domestic oil production, this implies an increase in oil imports.

3. Natural gas use will remain constant to the turn of the century thanks to increased imports.

4. Coal is expected to be the switch fuel whose usage will continue to increase as oil and gas prices escalate with increased competition for remaining supplies. Proved coal reserves represent 87% of remaining fossil fuels in the U.S.

5. The role of nuclear energy will be limited in the foreseeable future since any additions would have to at least be in the permitting stage in order to impact the U.S. energy situation in the next 30 years.

6. Transportation fuels remain the nation's Achilles' heel.

Therefore, the future need for clean fuels from coal, oil shale and tar sands are obvious, to reduce our energy imports and ensure a stable domestic supply.

Underground coal gasification is one of the most promising methods to convert our huge coal reserves to clean gaseous and liquid fuels at costs competitive with current commercial sources. Successful implementation of underground coal gasification is expected to triple U.S. coal reserves, allowing us to tap enormous coal deposits that are unattractive for conventional mining.

THE UNDERGROUND PROCESS

Underground coal gasification is similar to conventional or surface gasification except that the coal is not mined and gasified in a surface gasifier. Instead, the coal bed is prepared by drilling and linking process wells, and the coal is gasified in place.

Steam and oxygen reactants are preferred to air so that nitrogen is not introduced as a diluent and the gas can be used to produce a wide variety of products, such as methanol, gasoline, ammonia, or oxygenated chemicals. In addition the gas can be burned to produce process heat or electricity. (Fig. 1).

The principal reactions, which are typical for any coal gasification process, include:

Pyrolysis:	coal $\rightarrow$ char + tar + H_2O + gases
Oxidation:	$C + O_2 \rightarrow CO_2$
	$C + 1/2\ O_2 \rightarrow CO$
Gasification:	$C + H_2O \rightarrow CO + H_2$
	$C + CO_2 \rightleftharpoons 2\ CO$
Water gas shift	$CO + H_2O = CO_2 + H_2$

Coal in place is too impermeable for underground gasification to proceed. Therefore a connecting channel, or link, must be prepared between process wells. One method of preparing a channel is by reverse combustion. The coal is ignited at the bottom of the production well, while air is forced into the injection well, flowing to the production

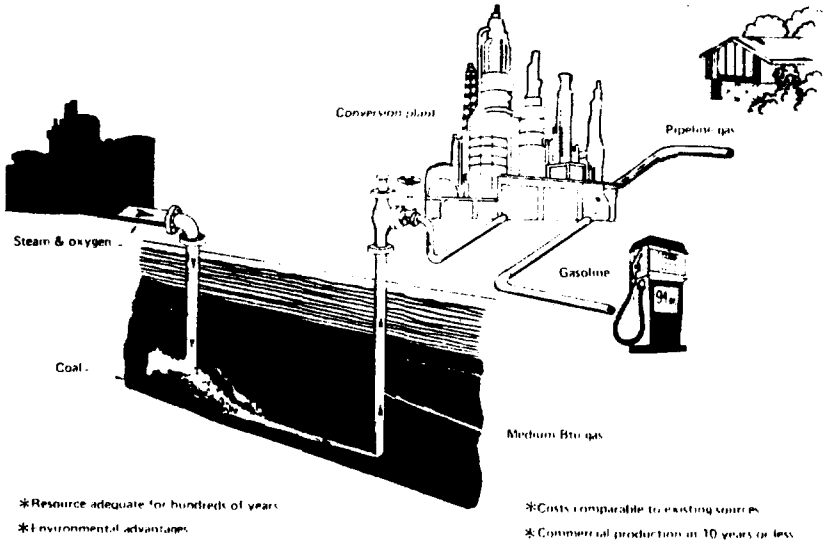


Figure 1. Underground coal gasification (UCG) is a promising new source for fuels.

well through natural fractures in the coal. The burn front is drawn by conduction toward the source of oxygen, burning a narrow channel in the direction countercurrent to the flow of air--hence the name reverse combustion.

The advantage of this method is that it is inexpensive for shallow (less than 1000 ft deep) coal. Its disadvantage lies in the often unpredictable path the link may take as it follows fractures and other natural inhomogeneities in the coal seam.

Another effective way to connect the injection and production wells is with a horizontal hole drilled in the coal seam (Fig. 2). Such a hole can be drilled from the surface using the technique of directional drilling.

Drilled holes for linkage have the advantage of reliability; the linkage path is known. However the directional requirements for UCG are at the state of the art and present costs are higher than for reverse combustion.

After the wells are connected, the coal at the bottom of the injection well is ignited (Fig. 2a). Air or a mixture of oxygen and steam is injected to support gasification, and the fire travels slowly through the coal bed toward the production well on a broad front, consuming the coal and producing valuable gaseous products.

An alternative, new technique, shown in Fig. 2b, is called the controlled retraction injection point, or CRIP method.

As a UCG cavity initially develops, the product-gas heating value, chemistry, and thermal efficiency are all excellent. When the burn reaches the roof, heat losses begin, with a corresponding decline in gasification performance and in economics. The amount of decline is acceptable at sites with strong dry roof material but is less acceptable at sites with a wet weak overburden. The CRIP method was developed to minimize these heat losses (Hill and Shannon, 1981). The concept requires a drilled hole for linkage as shown in Fig. 2b. A liner, inserted through the injection well casing until its tip reaches a position near the intersection point with the production well, carries the injectant, either air or oxygen/steam. As the burn cavity grows larger, it eventually intersects the roof of the seam and roof collapse begins. At some point the heat lost to the roof material begins to significantly degrade the gas quality. When this

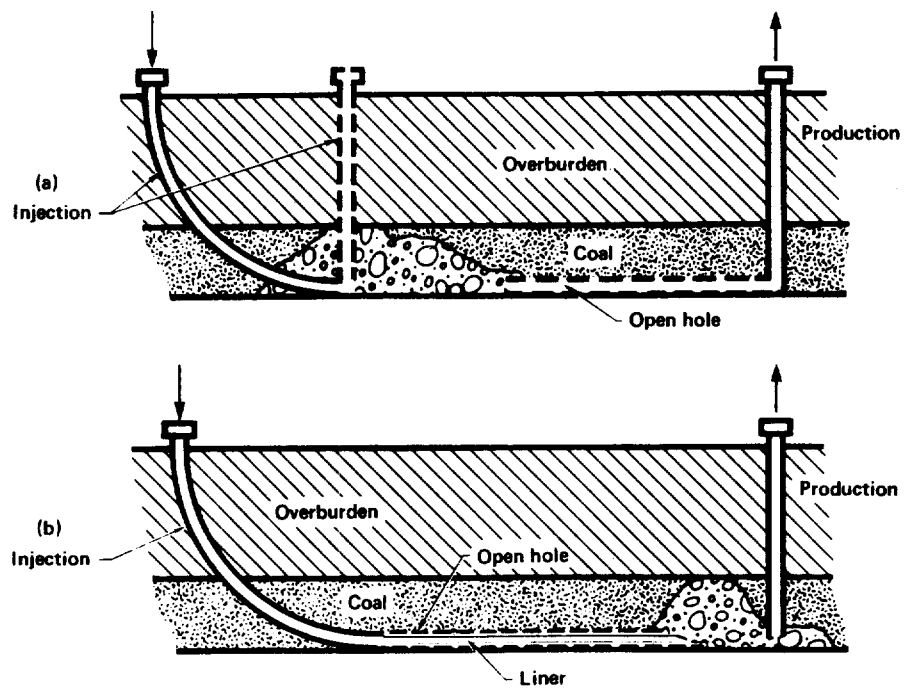


Figure 2. Underground coal gasification using directional drilling: (a) fixed air/oxygen injection point, (b) controlled retracting injection point.

happens the injection point is retracted in the upstream direction by burning off a section of the injection liner with the igniter. The coal opposite the burned zone ignites and a new cavity starts to grow. Since the high temperature zone is once again entirely within the coal, the heating value of the product gas will rise back to its original value. The CRIP concept involves a repetition of this process over and over again, drawing the burn step by step, in a controlled manner, upstream from the original injection point.

It is important to locate the connecting channel between the wells near the bottom of the seam. Low rank coals such as subbituminous and lignite shrink and fall apart on heating, so the coal immediately above the gasification zone falls to the bottom, creating an underground packed bed of coal. Thus the burn consumes the bottom as well as the top of the coal bed, utilizing almost all the coal.

A combination of convective and dispersive effects in the thermally evolving system causes lateral movement of oxygen and/or thermal energy out to a considerable distance from the ignition point, which accounts for the experimentally observed wide gasification zones (60 to 100 ft wide in low rank coal with 100-ft spacing between injection and production wells). A commercial UCG operation would employ a large number (up to 100) of injection-production well pairs like the pairs in Fig. 1-2, operating simultaneously in a system. Each well pair would consume about 100 tons of coal per day, producing some 5 million standard cubic feet (scf) per day of medium-heating-value gas.

Uncontrolled burns can be prevented by utilizing only those coal seams which lie below the natural water table, since stopping the injection allows water to invade the reaction zone and extinguish the fire. A certain amount of underground water is desirable for the steam-char reaction. However, most UCG sites contain more water than is needed, and excessive influx may degrade the product gas quality.

Figure 1 and 2 show gasification of flat-lying coal beds. However, the Soviet Union (Kreinin and Revva, 1966) and Gulf R&D (Davis, et al, 1982) have shown that steeply dipping coal beds can be gasified using similar methods with excellent results. Such steeply dipping beds, which are difficult to mine by conventional techniques, appear to be particularly applicable to UCG.

SITE SELECTION AND CHARACTERIZATION

The suitability of a coal deposit for UCG depends upon a number of factors, including market potential, ownership, institutional factors, and environmental/socioeconomic aspects (McSparran, et al, 1980). Only the coal type, depth, thickness, and geology/hydrology are considered here.

Low rank coals such as subbituminous and lignite are preferred over bituminous coal because they shrink upon heating, whereas bituminous coal swells and usually occurs in thinner seams.

The Soviet, British, and early U.S. experiments in UCG encountered severe problems while attempting to gasify coal seams 2 m thick or less (Gregg, et al, 1976). Heat losses are considerable with such thin seams, leading to low thermal efficiency and poor product-gas quality.

Minimum depths of 60 m for a seam 2 m thick and 90-120 m for a seam 6-9 m thick appear reasonable to avoid surface subsidence during gasification. The maximum depth is limited by economics.

A coal seam overlain by a strong, dry roof rock seems desirable to minimize heat losses and escape of gas to the overburden. Moreover, the coal seam should not be a major aquifer, nor should major aquifers be found above the coal for at least twice the stable cavity height. One wishes to minimize excessive water influx into the gasifier, whether from the coal itself or from aquifers above it which may connect into the reaction zone due to collapse of the intervening strata after a gasification cavity has been formed.

Site selection and characterization involve measuring the above parameters. Holes are drilled and logged, cores of the coal and overburden are taken for physical and chemical measurement, and hydrology and permeability tests are carried out in the coal seam and overburden. Some surface techniques also appear to be useful in delineating the coal and certain structural features (Bartel, et al, 1980).

UCG STATUS

The Soviet Union

The Soviet Union was the first nation to initiate UCG research, starting in 1931. After World War II, other nations participated in UCG research, including the USA, but with generally poor results. However, by the early 1950's the Soviets had evolved a successful UCG system, which was

applied in: (1) flat-lying beds in the coal fields at Tula and Schatska near Moscow and later at Angren near Tashkent, and (2) steeply dipping beds at Lisichansk in the Donets coal basin and at Yuzhno-Abinsk in Siberia. The results at Tula, Lisichansk, and Yuzhno-Abinsk were sufficiently encouraging that by 1958 plans were laid for significant production of energy through UCG. Annual production was projected to be 4.5 x 10^9 m^3/yr initially and was to be expanded by 41 x 10^9 m^3/yr. Because this occurred at a time (1958) when annual production from UCG was only 0.77 x 10^9 m^3/yr, this expansion is interpreted as an advance from demonstration to full-scale commercial deployment. In terms of annual coal consumption, the plan called for an increase from 300,000 tons of coal consumed in 1958 to 18 million tons annually.

The actual production never reach the ambitious projections. Lisichansk and Tula were shut down, at least partially due to exhaustion of coal sources. Actual Soviet production of UCG-derived product gas is shown in Fig. 3. (Stephens 1980). As can be seen, production peaked in 1966 at a little over 2 billion m^3 of product has that year.

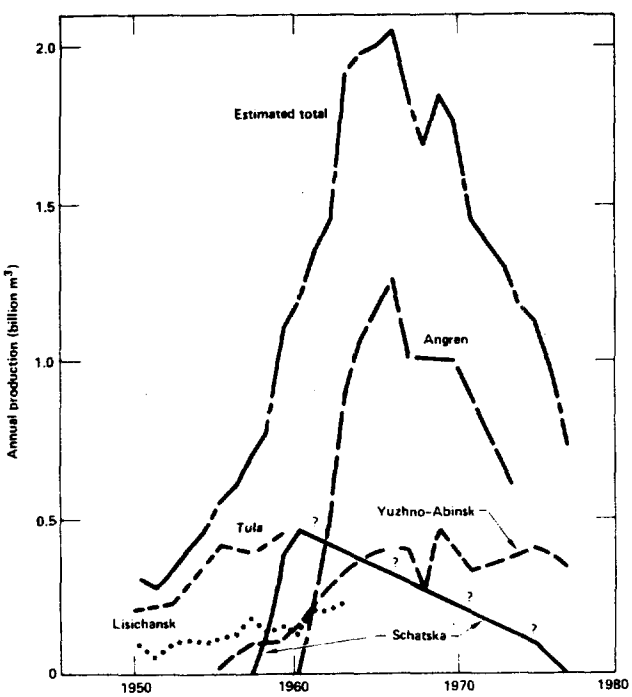


Figure 3. Annual Soviet UCG production, 1950-1977.

It is clear that something went wrong with the Soviet UCG development plans. The plans never were implemented, and after 1966 production from UCG declined and continued to decline at least until 1977. The reasons for this decline are not given explicitly by the Soviets, but one of the reasons may be the performance at Angren - poorer than was predicted.

The Soviets planned for 30- to 40-m wellbore spacings at Yuzhno-Abinsk (Kreinin and Revva, 1966) and 35m or even greater at Angren, (deCrombrugghe 1959) after their successful use of 25 to 30-m or larger spacings at Schatska. (Jensen, 1979; deCrombrugghe 1959; Svjagincev, 1979) Similar spacings are commercially attractive in the US.

These spacings may or may not have been achieved at Yuzhno-Abinsk. Kreinin and Revva reported wellbore spacings of 17 to 22 m and also 30 to 40 m at Yuzhno-Abinsk. Svjagincev reported an average wellbore spacing of 15 m.

Lavrov et al (1971) discussed possible wellbore spacings of 40 to 50 m at Angren using directional drilling to link the wells, but stated that in using reverse combustion vertical holes had to be drilled every 18 to 20 m (20 to 25 m according to the Alberta Research Council per Jensen) (Jensen 1979). Svjagincev identified the average wellbore spacing of 17 m at Angren. The Alberta Research Council trip report by Jensen as well as data from Golubev et al. (1965) make it clear that not all wells at Angren are used for gasification - some are used only for linking, and the desired gasification well spacings are 40 m or more. If the US emulated the closely spaced well at Angren there would be an economic penalty.

The product gas heating value for Angren was predicted to be 1000 kcal/m^3 - lower heating value (LHV). The average LHV at Schatska was 800 kcal/m^3 and Angren was expected to be greater due to the thicker coal seam of 9 m vs 2 m at Schatska, and more favorable hydrology. However, the Angren actual value was 800 kcal/m^3 identical to Schatska's LHV (see Table 1). Note that the Soviets quoted lower heating value. The LHV of 800 kcal/m^3 is approximately equivalent to 100 Btu/scf (higher heating value (HHV). The product gas heating value from Yuzhno-Abinsk as reported by Zvyaghintsev et al (1979) averaged out to a HHV of 119 Btu/scf, which is significantly higher than at Angren or Schatska.

Table 1. Soviet UCG Product Gas Compositions and Heating Value

Component	Podmoskovia	Schatska	Angren-expected	Angren-actual	Yuzhno-Abinsk
H_2	15.25	-	-	17.6-19.7	-
CO	5.95	-	-	4.5-7.5	-
CH_4	1.45	-	-	1.8-1.9	-
C_nH_m	0.27	-	-	0.2-0.3	-
CO_2	18.15	-	-	17-20	-
LHV[a] kcal/m^3	806	800	1000	760-860 (~100 Btu/scf)	- -
HHV[b] Btu/scf	88	100	126	93-112 [Av-96]	119

[a]LHV-Lower heating value.
[b]HHV-Higher heating value.

The Soviets reported 25% gas losses at Schatska but only 16 to 17% for Angren and Yuzhno-Abinsk (Zvyaghintsev et al, 1979). However, the Soviet and western methods for computing gas losses differ significantly. The common US practice is to assume that the gas composition lost (by nitrogen or other balances) is the same as the produced gas. The Soviets assume that the composition of the gas lost is 50% that of the outlet gas and 50% air, but with oxygen replaced by carbon dioxide. Thus, gas losses computed by the Western method are always larger than the losses computed by the Soviets. For example, the average gas loss given by Zvyaghintsev et al for Angren during 1962-1977 is 15.8%. However Belgian visitors (Jensen et al, 1979) obtained the raw data from which by nitrogen balance one calculates an average gas loss of 25%. Similarly, Zvyaghintsev et al. show average gas losses of 17.1% at Yuzhno-Abinsk compared to the 26% average calculated by Western methods. Gas losses provided a proportional cost penalty--a 25% gas loss means that the product gas cost 33% more than it otherwise would have.

These reported gas losses, close well spacings, and lower product gas qualities would produce unfavorable economics in the U.S. In addition, the Soviet Union at the same time were rapidly increasing their natural gas production and improving their open pit coal mining, so UCG faced stiff competition.

It is unfortunate that the Soviets made little use of underground diagnostics and modeling, and apparently ignored several innovations that were suggested in their own literature. Some of these, such as linking by directional drilling, are now being used in the U.S.

The U.S. program sponsored by the Department of Energy (DOE), in contrast to the more mature Soviet program, emphasizes modeling and subsurface instrumentation in an attempt to understand, and hence to achieve, better control of the underground process. Perhaps because of the success of these attempts to understand the process, the U.S. results have been more encouraging.

U.S. Program Status

Initial UCG activities in the U.S. were carried out by the U.S. Bureau of Mines in 1947-1960 near Gorgas, Alabama. The results were poor, and the program was terminated.

The U.S. government resumed its sponsorship of UCG field testing in 1973. Since that time 21 UCG tests have been carried out, 16 of which were funded by the federal government. Test results are summarized in Tables 2 and 3. Results from tests at the same site tend to be consistent. Site selection plays a major role in gasification quality. Sites with relatively dry, strong overburden and at least moderately thick coal produce favorable results. These examples include the Hanna, Rawlins and Centralia sites. Sites with thin coal or containing wet, weak overburden produce less favorable results, as the Hoe Creek or the Texas tests.

Table 2. Summary of U.S. DOE-sponsored UCG field tests (forward gasification phase).

Test	Year	Duration (days)	Coal consumed (tons)	Gas quality (Btu/scf)	(MJ/m^3)	Cold Gas* thermal efficiency (%)
Laramie Energy Technology Center -- Hanna, Wyoming, site						
I	1973-1974	168	2720	126	4.7	77
II-1A	1975	37	962	137	5.1	85
II-1B	1975	38	780	143	5.3	86
II-II	1976	26	2201	168	6.3	92
II-III	1976	39	3414	132	4.9	77
III	1977	38	2663	138	5.1	77
IV-A(a)	1978	7	294	109	4.1	78
IV-A(b)	1978	48	3184	102	3.8	73
IV-B(a)	1979	7	468	149	5.5	95
IV-B(b)	1979	16	663	122	4.5	83
Lawrence Livermore National Laboratory -- Hoe Creek, Wyoming, site						
I	1976	11	123	101	3.8	82
II(air)	1977	13	286	108	4.0	80
II(O_2)	1977	2	47	263	9.8	88
II(air)	1977	43	1155	104	3.9	74
III(air)	1979	7	256	113	4.2	81
III(O_2)	1979	47	3251	212	7.9	73
Centralia, Washington, Site						
LBK(O_2)	1981-82	20	140	262-284	9.8-10.6	80
(air)				140	5.2	
CRIP(O_2)	1983	28	2000	248	9.2	74
Morgantown Energy Technology Center -- Pricetown, West Virginia, site						
I	1979	17	234	149	5.5	97
Gulf Research and Development Co. -- Rawlins, Wyoming, site						
I(air)	1979	30	1207	151	5.6	91
I(O_2)	1979	5	125	250	9.3	74
II(O_2)	1981	66	8550	330	12.3	88

*Ratio of heating value of gas to heating value of the coal used in deriving the gas.

Table 3. Privately sponsored UCG field tests in USA.

Test	Year	Duration (days)	Gas quality (Btu/scf)	MJ/m^3	Coal gasified (tons)	Cold gas thermal efficiency (%)
Basic Resources, Inc.						
Fairfield, TX	1976	26	126	4.7	--	--
Tennessee Colony, TX:						
Air injection	1978-79	197	81	3.0	4000-5000	--
Oxygen injection		10	230	8.6	212	--
ARCO Coal Co.						
Reno Junction, WY	1978	60	200	7.4	3600	94
Texas A&M University (with Industrial Consortium)						
College Station, TX	1977	1	35-114	1.3-4.2	2	--
Bastrop County, TX	1979	2	85	3.2	--	--
Bastrop County, TX	1980	--	35-150	1.3-5.6	--	--

The present low prices for oil and gas have reduced commercialization interest for UCG, as it has for all synfuels. However, at least two programs are active:

Basic Resources, Inc., a subsidiary of Texas Utilities, purchased the U.S. rights of the Soviet UCG technology in 1975, and, after conducting a number of tests in Texas lignite (Haney 1979; Grant and Fernbacher 1979) (Table 2) has designed and is in the construction phase of an electrical generating demonstration plant (7 MWe capacity).

The Gas Research Institute leads an industrial consortium in sponsoring, with the U.S. DOE, a large-scale UCG test at Centralia, Washington to demonstrate the CRIP and other UCG methods. The test will employ steam-oxygen gasification using dual injection and production wells. Gasification is presently planned for the late fall of 1986. This test follows the successful Centralia Partial Seam CRIP test, which is described in the next section.

The Partial Seam CRIP Test

The partial seam CRIP test was carried out in a 19-foot thick subbituminous coal seam near Centralia, Washington, during October - November 1983. It was conducted by the Lawrence Livermore National Laboratory, in cooperation with The Washington Irrigation & Development Co., under the sponsorship of the U.S. Department of Energy and the Gas Research Institute.

A schematic of the test is shown in Fig. 4 while plan and elevation views of the coal and process wells are shown in Fig. 5. Instrumentation wells containing thermocouples and TDR (time domain reflectometry) cables are also shown in Fig. 5.

The injection well was drilled from an exposed coal face near the bottom of the seam for a distance of 900 ft. Two production wells were employed, a vertical well near the end of the injection well and an inclined production well, which slanted through the overburden down into the coal. The slant production well crossed near the injection well but did not connect to it, while the vertical well was mechanically connected to the injection well prior

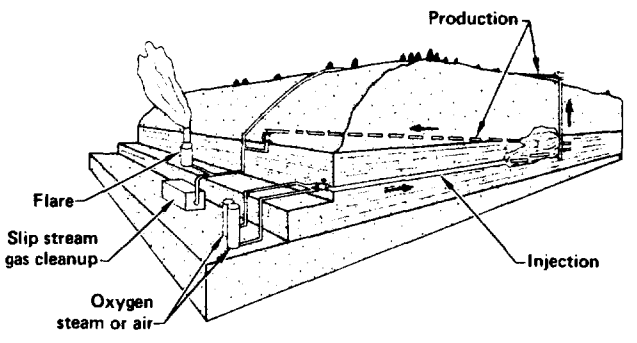


Figure 4. Planned layout of the Centralia partial seam CRIP test. Slant injection and production wells were drilled 900 ft from the coal outings. A vertical production well was drilled 225 ft to the 20 ft thick upper section of the Big Dirty coal seam.

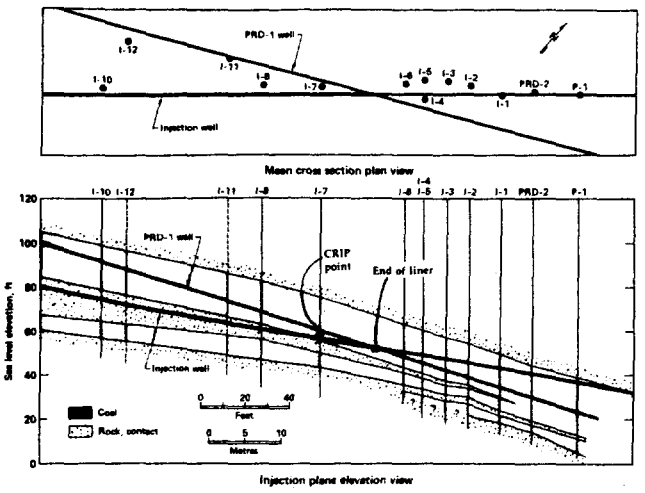


Figure 5. Layout of instrumentation, production, and injection wells for CRIP test at the WIDCO mine near Centralia, Washington. The burn was started at the end of the liner and the gases were drawn off through vertical production well PRD-2 and later through the slant production well. About midway through the gasification the injection point was retracted to the CRIP point where a new burn was started. Instrumentation wells are designated I-1, I-2, etc. P-1 was a pump well.

to the burn. As gasification proceeded, the slant production well connected to the burn cavity.

The coal seam was ignited on October 16, 1983. Good product gas was obtained with steam-oxygen injection. Air was injected for brief periods when power outages occurred or when the steam boiler needed repairs.

The vertical production well was used until October 28, when the slant well was connected to the cavity and we switched to it. We observed an improvement in product gas quality upon changing to the slant well, and the entire changeover went smoothly. On October 30 the controlled retraction maneuver was executed and a new cavity was successfully established.

We continued steam/oxygen gasification using the new cavity and the slant production well until November 14, 1983, when the experiment was shut down. Figure 6 shows the product gas heating value for the burn period, and Figure 7 shows some of the product gas chemistry. Minima in heating value, H_2 and CO composition correlated with injection of air, rather than steam and oxygen, forced by the boiler failures and power outages mentioned previously. Interaction of the burn with the roof can be seen during days 6-12 for the first cavity and during days 22-29 (November 7-14) for the second. The slant production well was used beginning on day 12 (October 28), and an increase in product gas quality can be seen. The CRIP maneuver was executed on day 14.

Three distinct gasification periods can be observed. The initial period, in which the vertical production well was in use, yielded a typical dry-gas heating value of 248 Btu/scf. This was followed by a period of considerably higher gas quality, 296 Btu/scf, which resulted from the switch to the slant production well and the CRIP maneuver. The final period began when a large-scale underground roof fall occurred and the typical dry-gas heating value decreased to 220 Btu/scf (Cena et al, 1984).

Approximately 670 tons of coal were gasified with the first cavity and 1330 tons during the second, for a total of 2000 tons.

Major results for the steam-oxygen injection periods are given in Table 4.

Burn cavity contours were estimated for various times during the test, using on-line thermal and subsidence instrumentation, total coal consumption by material balance, process performance and modeling. The contours are shown in Fig. 8. The final contours were essentially verified by post-burn coring (Dana, Covell, et al 1984).

Our major conclusions from this underground coal gasification test are:

(1) The Centralia site is favorable for underground coal gasification (UCG).

(2) The small-scale Large Block tests, which we conducted two years ago at the same site, produced similar results as the much larger scale partial seam test.

(3) Use of a slant production well is advantageous for UCG.

(4) The controlled retraction injection point method (CRIP) was successfully tested, with an improvement in UCG performance.

Foreign Programs

UCG field testing has been carried out in France (Gadelle et al, 1984) and Belgium.(Patigny et al, 1984) Due to the use of thin (2m) seams at great depth (up to 1000 m), the projects have been thus far unable to proceed to forward gasification.

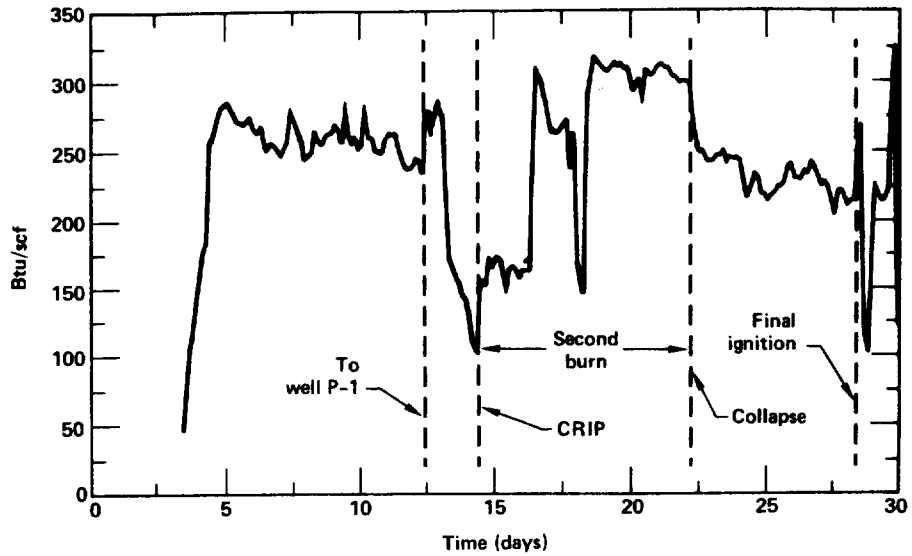


Figure 6. Product gas quality (heat of combustion) as a function of time for the entire test. Minima are due to air injection forced by power outages and boiler repairs.

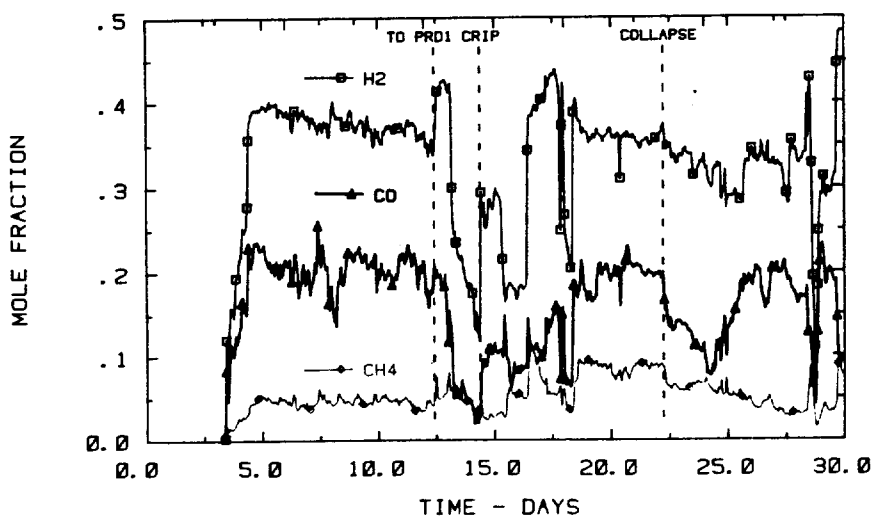
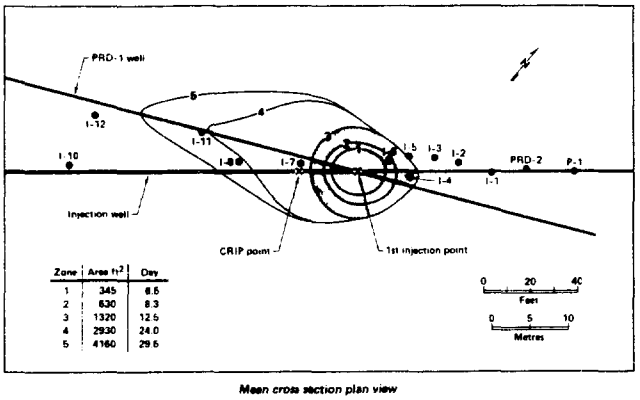


Figure 7. Variation in the proportions of the three principal combustible components in the product gas. Gas composition is strongly dependent on reaction temperature. Heating value is strongly influenced by the amount of hydrocarbons (e.g., methane) present. Minima are due to air injection forced by power outages and boiler repairs.

Table 4. Partial Seam CRIP Test Summary Average Values During Steam-Oxygen Gasification (October 16-November 14, 1983)

Dry Product Gas Heating Value	248 Btu/scf 9.2 MJ/m^3
Coal Gasified	2000 tons
Dry Gas Composition (vol%)	
H_2	36.1
CH_4	5.4
CO	18.5
CO_2	36.1
C_nH_m	1.0
H_2S	1.6
N_2 & Ar	1.3
Product Gas mol Ratio	
H_2O/Dry Gas	1.3
Thermal Efficiency %	74



Mean cross section plan view

Figure 8. Approximate burn cavity contours at selected times during the Partial Seam CRIP experiment. Approximately 670 tons of coal were gasified from the first cavity and 1330 tons from the second, for a total of 2000 tons.

Linkage attempts have been made using reverse combustion in Belgium and hydraulic fracturing followed by reverse combustion in France.

The U.S. Department of Energy entered into two recent agreements to transfer UCG technology from the U.S. to the governments of Brazil and Spain.

Brazil has an abundance of very poor quality, high ash coal which, however, may be suitable for UCG. This is of great interest to Brazil due to its high import bill for crude oil.

The Spanish government is presently considering sponsorship of an UCG program. Spain has considerable resources of coal suitable for UCG and is paying high prices for imported natural gas.

ENVIRONMENTAL CONSIDERATIONS

The principal environmental issues for UCG are water contamination and subsidence. Subsurface ground motion occurs in all UCG experiments. In US experience, the cavities collapse, in general, to a distance of two coal seam thicknesses or less. The Soviet tests exhibited surface subsidence due to their larger scale and closely spaced process wells (Gregg, et al 1976).

Both inorganic and organic contaminants are introduced into the coal aquifer and possibly into overlying aquifers following UCG. The inorganics are confined to the cavity water and are derived from coal ash and heated overburden filling the cavity. Persistent inorganics include ammonium, fluoride, boron, sulfate and calcium. The cavity water chemistry is complex and is not well understood.

Organics, primarily phenols, appear to be deposited primarily near the edge of the burn cavity. Low but measurable amounts are found far from the cavity, probably transported by escaped product gas (Wang, et al 1982).

The concentration of both organic and inorganic contaminants tend to decrease with time, apparently due to dilution, dispersion, sorption and bacterial action. Contamination of aquifers above the coal has been minor.

Thus far the predictive capability for subsidence is good but is lacking for water quality. If water contamination persists, active aquifer restoration may be required. This is technically feasible for cavity water but would be extremely difficult for water beyond the burn zone.

At present the environmental effects of commercial UCG on water quality are uncertain. More data are needed, particularly with larger scale tests, to demonstrate acceptable environmental risk of UCG.

COST ESTIMATES

Product costs for a new technology such as UCG are difficult to estimate. The estimator must make assumptions about process uncertainties in making cost projections. The assumptions made are usually moderately optimistic; i.e., the process is assumed to work reasonably well.

Table 5 presents cost estimates from two sources: McCown et al (1982) for medium heating value gas, methanol and gasoline, and Hill, Burnham

Table 5. Cost Estimates for Underground Coal Gasification Products

	$/10^6 Btu	$/gal
Medium Heating Value Gas (250-300 Btu/scf	4.35	
Pipeline Quality Gas (950 Btu/scf)	5.19	
Methanol	9.19	0.52
Gasoline	10.20	1.39

et al (1984) for synthetic natural gas. The projected costs for medium heating value gas, synthetic natural gas, and methanol from UCG compare favorably with costs of the same products from existing sources, while gasoline from UCG exceeds the present price.

Bases for the costs differ. McCown et al assumed a 30% equity and a 20% discounted cash flow profit. Hill et al assumed a 35% equity and a levelized cost based on historical real returns on capital by the natural gas industry.

These estimates are "plant gate" prices, including producer's profit but excluding transportation, retail costs and exise taxes.

CONCLUSIONS

The technical feasibility of UCG combined with its favorable cost estimates indicate that it is one of the most promising methods to produce clean fuels from unminable coal. Successful implementation of the could more than triple the proved U.S. coal reserves. The UCG process appears to be environmentally acceptable.

At this stage of development, UCG is a high risk technology and will remain so until larger scale field tests are successfully carried out. These tests are recommended by the Gas Research Institute (Webb 1985) and by the American Institute of Chemical Engineers.(Hammesfahr, Edgar, et al, 1981) A seven year program costing about $200 million would permit initial commercial production in ten years. With the continued joint efforts of industry and government, UCG should make a significant impact on the U.S. energy technology.

REFERENCES

Bartel, L. C., Dobecki, T. L. and Stone, R., 1980, Results of the Characterization of an In-Situ Coal Gasification Site in the State of Washington: Proc. Sixth Underground Coal Conversion Symposium, pp. I-41 - I-48.

Çena, R. J., Hill, R. W., Stephens, D. R. and Thorsness, C. B., 1984, The Centralia Partial Seam CRIP Underground Coal Gasification Experiment, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-91252.

Dana, G. F., Covell, J., Oliver, R. L. and Elliott, J. R., 1984, Preliminary Results of Postburn Coring and Drilling at WIDCO - CRIP UCG Experimental Test Site, Centralia, WA: Proc. Tenth Underground Coal Conversion Symposium, to be published.

Davis, B. E., Ahner, P. F., Covell, J. and Singleton, A., 1982, Status of the Rawlins UCG-SDB Program: Proc. Eighth Underground Coal Conversion Symposium, (Keystone, CO, August 15-19, 1982) SAND 82-2355 (1982), pp. 205-212.

de Crombrugghe, O., 1959, Underground Gasification (of coal) in the USSR, U.S. Dept. Interior Translation TN7, E59, No. 394, from Annales des Mines de Belgique, No. 5, 478-534 (May 1959).

Edmonds, J. and Reilly, J., 1983, Energy 8 No. 6, 419.

Gadelle, C., Lessi, J., Marrast, J., Pottier, M., Raffoux, J. F., Sarda, J. P., and Ternot A., 1984, UCG Tests at La Haute Deule-First Results: Proc. Tenth Underground Coal Conversion Symposium, to be published.

Golubev, Yu. B., Zybalova, G. P., Petukhova, N. N., Schad'ko, A. M., 1965, Dynamics of Gas Formation During the Gasification of a Seam of Brown Coal in an Experimental Gas Generator at the Angren Podzemgaz Station, Tr. Vses. Nauch.-Issled. Inst. Podzemn. Gasifikatsii Uglei (13), 11-17 (1965) [English transl: UCRL-Trans-11051, Lawrence Livermore Laboratory].

Grant, J. F. and Fernbacher, J. M., 1979, Tennessee Colony Steam-Oxygen In-Situ Lignite Gasification Test: Proc. Fifth Underground Coal Conversion Symposium, CONF 790630, 109-117.

Gregg, D. W., Hill, R. W. and Olness, D. U., 1976, Overview of the Soviet Effort in Underground Gasification of Coal, Lawrence Livermore National Laboratory Report, Livermore, CA, UCRL-52004.

Hammesfahr, F. W., Edgar, T. F., Gunn, R. D., Meyer, H. S., Singleton, A. H. and Zey, A. F., 1981, Underground Coal Gasification, report of the task force to the Government Programs Steering Committee, American Institute of Chemical Engineers, December 18, 1981.

Haney, S. E., 1979, Tennessee Colony In-Situ Gasification Project -- A Review: Proc. Fifth Underground Coal Conversion Symposium, CONF No. 790630, 103-108.

Hill, R. W. and Shannon, M. J., 1981, The Controlled Retracting Injection Point (CRIP) System: A Modified Stream Method for In-Situ Coal Gasification, Lawrence Livermore National Laboratory Report, Livermore, CA, UCRL-85852.

Hill, V. L., Burnham, K. B., Barone, S. P., Rosenberg, J. I., Ashby, A. B., 1984, Underground Coal Gasification: Its Potential for Long-Term Supply of SNG, Gas Research Insights, The Gas Research Institute, Chicago, IL., February 1984.

Jensen, E. J., 1979, Visit to the USSR by the Gas Working Group, (Alberta Research Council), (January 15-22, 1979); included is the September 1975 Belgian report: "Underground Coal Gasification," a report by Institut National des Industries Extractives of Belgium on the visit of a Belgian delegation to Russia.

Kreinin, E. and Revva, M., 1966, Underground Gasification of Coal, Podzemnaya gazifikatsiya uglei. Kemerovskoe knizhnoe izdatel'stvo [English transl.: UCRL-Trans-10810, Lawrence Livermore Laboratory].

Lavrov, N. V., Kulakova, M. A., Kazachkova, S. Ts., Zhirnyi, A. E., Antonova, R. I., Volk, A. F., 1971, Underground Gasification of the Angren Brown-Coal Field, Khimiya Tverdogo Topliva, (1), 73-79 (1971) [English transl.: UCRL-Trans-10922, Lawrence Livermore Laboratory].

Lavrov, N. V., Kulakova, M. A., Kazachkova, 1971, An Analysis of Several Technical Factors in the Underground Gasification of Brown Coal, from Moscow Vses. Nauch-Issled. Inst. Podzemn. Khraneniya Nefti, Nefterproduktov I Szhizhennykh Gazov. Tr. Inst. I Proizvodstvennyi Opyt., (5), 133-137 (1971) [English transl.: UCRL-Trans-10979, Lawrence Livermore Laboratory].

McCown, P. J. and Smith, G. W., 1982, Underground Coal Gasification (UCG) -- Gas to Methanol and MGT Gasoline: An Economic and Sensitivity Study: Proc. Eighth Underground Coal Conversion Symposium, SAND 82-2355, 499-510.

McSparran, D. K., Follick, J. H. and Tate, James Jr., 1980, Major Environmental and Sociopolitical Issues to be Resolved Before UCG is Commercialized: Proc. Sixth Underground Coal Conversion Symposium (Shangri-La, Okla., July 13-17, 1980), CONF. NO. 800716, pp. II-59 - II-63.

Parent, J. D., 1984, Institute of Gas Technology, 4 Energy Topics, April 2, 1984.

Patigny J., Li T.K., Chandelle V., Sonntage C., Fabry R. and Kurth M., 1984, Status of the Joint Belgo-German Experiment of Underground Coal Gasification: Proc. Tenth Underground Coal Conversion Symposium, to be published.

Stephens, D. R., 1980, An Appraisal of Soviet Underground Coal Gasification: LLNL In-Situ Coal Gasification Project Quarterly Progress Report January through March 1980, Lawrence Livermore National Laboratory Report, Livermore, CA, UCRL-50026-80-1, 2-7.

Stephens, D. R., Hill, R. W., and Borg, I. Y., 1985, Status of Underground Coal Gasification, Mineral Processing and Technology Review (in press).

Svjagincev, K. H., 1979, Underground Coal Gasification in the Soviet Union, Gluckauf 115 (No. 11), 540-546 (1979). [English transl.: UCRL-Trans-11556, Lawrence Livermore Laboratory].

Wang, F. T., Mead, S. W. and Stuermer, D. H., 1982, Mechanisms for Groundwater Contamination by UCG - Preliminary Conclusions from the Hoe Creek Study: Proc. Eighth Underground Coal Conversion Symposium, SAND 82-2355, 399-410.

Webb, D., 1985, Testimony to Committee on Science and Technology, U.S. House of Representatives, March 6, 1985.

Zvyagintsev, K., Kreinin, E. and Orlov, G., 1979, Underground Gasification of Deep Coals, IGU/B4-79, 14th World Gas Conference, Toronto, Canada.