AN ASSESSMENT OF UNDERGROUND IN-SITU COAL GASIFICATION IN WYOMING

A special report compiled for the exclusive use of the State of Wyoming by Daniel N. Miller, Jr., State Geologist of Wyoming, August 15, 1978.

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Preface

There are literally hundreds of technical reports and publications available to the public on the subject of coal gasification. More than half of these address the subject of underground in-situ gasification from the standpoint of engineering and technology. The intent of this report is to offer a personal assessment of the art of gasification based on these publications with particular emphasis on the role that it may play in Wyoming's future. Every effort has been made to condense the voluminous material available. A selected cross-indexed reference list is appended for the reader who may desire additional information on a particular aspect of the subject.

Introduction

Attempts to convert coal into usable combustible gaseous fuel have been carried on for more than 100 years (1) wherever coal is abundant. The tendency has been to mine the coal that is most readily accessible and then attempt to recover whatever combustible part of the coal lies beyond the practical economic limit of mining by some other method. Underground, in-situ, coal gasification then is an effort to recover a marketable fuel from an otherwise unavailable coal resource. Present technology involves the drilling of holes from the surface through the coal bed(s). The coals are then ignited by an electric or propane heater and combustion is maintained by the injection of air or oxygen (or combinations) under pressure. As the surrounding coal heats up to temperatures of several hundred degrees centigrade, certain volatile constituents are driven ahead into the coal bed itself as gases. By drilling other holes nearby, in order to offer escape routes, some of the gases can be recovered at the surface. The ultimate objective is to recover gases with a high enough Btu content and in sufficient volume to make the cost of the project worthwhile. Although there are alternative uses that the produced gas could be used for, its value as a low cost fuel in electrical generating plants (on site) seems to dominate the current thinking.

At present, and perhaps for the next several decades, it is unlikely that low Btu gases recovered from in-situ operations will be able to compete economically with other conventional fuels. There simply is no justification at present to enter into full-scale commercial operations for in-situ gasification. It is important to recognize, however, that as an alternative to the continued price increases of other fuels, or in the event of a national fuel crisis, underground gasification of coal offers at least a form of substitute supplemental fuel supply. In that sense, and with the understanding that it may take at least ten more years of experimentation to perfect an efficient commercial gasification technology, the nation should probably pursue research of this type. In all probability, entirely new and different kinds of fuel technology will advance more rapidly than will coal gasification. The fact is, that there is an abundant supply of readily available, low cost coal throughout the United States; more than enough to meet the nation's needs in the future. Whether or not this readily minable coal is put to its most effective use as boiler fuel depends almost entirely on the actions taken by the Congress.

Status of In-Situ Gasification Technology

Concepts regarding in-situ gasification (1) have not improved substantially on the early work originally begun by Sir William Siemans (1868), Dmitriy Ivanovich Mendeleyev, and an American named A. G. Betts, or the later work of Sir William Ramsey prior to World War I. In every case optimistic accounts were presented forecasting a fuel for the future without the hazards and hardships of mining. During and after the war, Russian scientists planned and carried out several successful experiments that eventually lead to substantial government funding and greatly increased interest in the early 1930's. Practically every kind of in-place combustion technique was tried to increase and decrease temperatures and pressures, augment and curtail permeability, or to change the chemistry through the introduction of oxygen, steam and water in different combinations. In addition, extensive laboratory experiments were carried out between 1932 and 1934 on block coal, crushed coal, pulverized coal, etc., in different chemical environments to test various aspects of vaporization and carbonization theory. Subsequent short-term, underground borehole experiments between 1935 and 1939 had varying degrees of success even to the point of operational pilot plants that fueled buildings and facilities for several months. An experimental gas turbine for use with electrical power plant generators was tested during 1939. The experiments terminated as the result of the German invasion and the beginning of World War II. Similar experiments, some of which were much longer term, were conducted in Poland and Czechoslovakia.

Following the war other national priorities precluded significant experimentation in Russia. It was apparent by 1950 that the processes involved in underground gasification were inefficient and could not be competitive with other fuels such as petroleum and natural gas.

Between 1946 and 1958, the U.S. Bureau of Mines, working at Gorgas, Alabama, conducted experiments modeled after the Russian's with modifications. It was obvious because of the widespread distribution of coal in the United States that there was a vested interest here in any in-situ system that could offer an economic alternative to other sources of fuel. Federal funding became available for research and experimentation through the Bureau and later through successor organizations ERDA and DOE. These agencies have in turn contracted with Lawrence Livermore Laboratory (LLL), Sandia Albuquerque Laboratories, and others, and in some cases like the Laramie Energy Research Center (LERC), and Morgantown Energy Research Center (MERC) conducted their own experimental operations. Gulf Research and Development, ARCO, and other industrial operators have also been active in this field.

Since the early 1960's, federally financed, in-situ research has been pursued in America through four separate programs: the Linked Vertical Well Process (LERC Group) - consisting of two stages, a reverse combustion step that links permeability in two nearby wells to create a path in the coal seam through which gases may flow, and a second step that is the forward gasification stage; the Explosive Fracture and Packed Bed Process (LLL Group) - wherein attempts are made to take advantage of the natural permeability that is then enhanced by introducing additional random fractures through the use of explosives intended to directionally distribute permeability in a more predictable manner. A steam-oxygen mix is then injected to upgrade the recoverable gases.

The Directed Drilling and Longwall Generator Process (MERC Group) - is designed to employ directional drill holes that extend along the coal bed rather than through it. In theory at least, batteries of parallel wells are to be drilled that attempt to align positive permeability routes, more or less paralleling the natural bedding planes of the coal. The concept employs a controlled combustion-gasification front that is maneuvered through the coal bed in alternate drill holes, with gas recovery through other drill holes between the combustion zones.

A fourth program called the Steeply Dipping Beds Program was also designed for testing that would have application where the coal seams are steeply inclined. The technique now being tested by Gulf near Rawlins, Wyoming, employs one or more wells that penetrate the coal seam at some predetermined depth where combustion is initiated and where air (steam and/or oxygen) is introduced, in combination with one or more drill holes that penetrate down the inclined coal bed to provide escape routes for the gases.

At present, aspects of all four of these experiments are still under consideration and/or investigation by federal agencies, contract researchers, and industry. No one program has as yet progressed to a full-scale pilot operation.

Underground Gasification Criteria

Based on previous performance there is a consensus among the engineering experts that the lower ranks of coal (lignite, subbituminous, and low volatile bituminous) will offer the best opportunities for underground gasification. There are extensive deposits of this type of coal throughout the northern Great Plains and Rocky Mountain states. In anticipation of commercial scale development the coals should be greater than 10 feet thick, separated from each other by impervious shale, and be available in depth ranges of 300 to about 1000 feet according to the engineers. Resource homogeneity over a significant area of at least several square miles is essential. Vertical fracturing, joints and faulting that could otherwise allow uncontrollable avenues of pressure and fluid escape are not desirable. Within Wyoming there are vast areas where the underground coal beds meet these criteria, and because of this the Laramie Energy Research Center, Lawrence Livermore Laboratory and ARCO have used sites in Wyoming for their underground experiments.

There are, however, other important criteria that heretofore have not been mentioned in previous experimentation because the efforts have been directed at the technology of gasification rather than more distant objectives of commercialization.

Wyoming Coal and In-Situ Gasification Experiments

Discounting competitive fuel economics and other factors that would influence commercial scale underground gasification of coal, there are vast areas in Wyoming that meet the minimal standards of engineering criteria.

In other words, when viewed from a research point of view there are essentially limitless sites that could be available in Wyoming for experimental purposes. Within the ten major coal regions of Wyoming occurrences of coal vary from the 10 separate seams within a 1200 ft. stratigraphic interval in the Hams Fork Region to individual coal beds up to 220 ft. thick in the Lake DeSmet area of Johnson County. The majority of the coals rank as subbituminous (c) although there are bituminous as well as lignite deposits in the State. Representative sampling has been done on the more significant seams in and around areas presently being mined, and the results are available at the Wyoming Geological Survey office in Laramie. In addition, the U.S. Geological Survey, U.S. Bureau of Mines, and the Illinois Geological Survey and the mining companies also have extensive analytical data on Wyoming coals. From the standpoint of basic coal chemistry there is very little difference that would significantly affect gasification, although some coals are subject to swelling.

Other geological information relating to coal occurrences including depths to seams, stratigraphy and structure is also known in a general way, and is available in the offices of the Wyoming Geological Survey and the U.S. Geological Survey. Specifics regarding any particular site or seam may or may not be available depending on individual circumstances.

Two separate underground coal gasification experiments (2) have been conducted in Wyoming within the past five years. The sites for experimentation were selected based on existing knowledge made available through the mineral and mining industry of Wyoming supplemented by additional drill hole data.

Powder River Basin - Packed Bed Process (Lawrence Livermore Laboratory)

Field work has begun during the winter of 1974-1975 consisting of five bore holes to determine the chemical and physical properties of several different seams. Cores, geophysical logs and other data were obtained and analyzed, and it was established that the Felix Coal at the Hoe Creek site in the western part of sec. 7, T. 47 N., R. 72 W., Campbell County, offered the best opportunity for preliminary hydrologic and gasification experiments on an isolated federally owned tract. The Felix seam(s), Nos. 1 and 2, are a part of the 47 million year old Eocene Wasatch Formation. Three bore holes were drilled and/or cored to depths of 50, 67, and 72.8 meters, sufficient to penetrate the lower and thicker Felix No. 2 seam which is about 7.6 meters thick, and occurs at depths between 38.7 and 50 meters. The overlying Felix No. 1 seam about 3.5 meters thick, was encountered in all three of the bore holes. Core descriptions of the No. 1 and No. 2 seams as well as the encompassing strata were obtained. In addition, the joint-fracture (cleat) patterns of other coals were analyzed in an effort to establish the most effective permeability routes (directions). Oriented cores of the Felix No. 2 coal at the Hoe Creek site indicated a preferred face cleat azimuth of N. 70° E.

Analyses of the Felix No. 2 coal obtained from cores at three nearby sites had the following compositions:

Ultimate analysis % (Dry)	Hoe Creek No. 1	Hoe Creek No. 2	Hoe Creek No. 3
Moisture	---	---	---
Carbon	68.08	69.23	66.42
Hydrogen	5.14	5.24	5.28
Nitrogen	1.28	1.45	1.30
Chlorine	0.00	0.00	0.01
Sulfur	1.54	0.49	0.63
Ash	7.87	5.80	9.76
Oxygen (diff.)	16.09	17.79	16.60
Btu content			
As received	8,326	8,359	8,285
Dried	11,850	11,960	11,469

Sulfur content ranged from 0.34 to 1.54 percent.

The Hoe Creek No. 1 experiment lasted 11 days and was conducted in mid-October 1976. Multiple explosive charges were used to enhance fracturing, and hopefully permeability, within the Felix No. 2 coal at a subsurface depth of 125 feet. Comparison of fracture analyses showed that permeability was increased from 0.3 darcies before fracturing, to 2 - 4 darcies after fracturing.

Twenty-eight hours after ignition of the coal, a permeability by-pass developed that channeled the burn to the top of the seam. Upon completion, the LLL group concluded that spherical high-explosive shots at the base of the coal seam did not produce a permeability distribution suitable for successful gasification. They concluded further that explosions within the coal itself tends to disintegrate the coal too much and generates fine particles that tend to bridge and clog the fractures, thereby reducing permeability. These same fine particles of coal, coated with tar, also plugged several of the orifices in the instruments being used to measure gas emission.

Although combustible gases were produced in conjunction with this experiment, the results are not particularly important. The primary objective of this experiment was to develop and demonstrate the ability to predict permeability enhancement through use of explosives, and this was not accomplished. Additional experimentation is planned for the future.

Hanna Basin - Linked Vertical Well Process (Laramie Energy Research Center)

In the fall of 1972 the U.S. Bureau of Mines began an underground coal gasification experiment (3) in the vicinity of sec. 29, T. 22 N., R. 81 W., Carbon County, on land owned by Rocky Mountain Energy Company. Based largely on extensive experimentation by the Russians nearly fifty years ago, this particular experiment was an American effort to develop a two-stage underground gasification process between nearby bore holes. The first stage is a reverse combustion step that links (connects through permeability channels) the bore holes and provides a path for combustion; and a second stage that is the forward gasification stage (4). In stage one, two or more bore holes are drilled 50 to 60 feet apart. The coal is ignited in one hole and oxygen (or mixtures of air, steam and oxygen) are introduced in the other. Combustion then travels through the coal bed in the direction of the oxygen. Pyrolysis occurs in the coal and produces small permeability channels. Once a "linkage" is established the role of the bore holes is reversed and forward gasificiation is established and controlled through the char channels. An effort is made to maintain the linkage at the bottom of coal bed so that continual collapsing of the roof occurs, the fresh coal is added, as the underlying coal is consumed. In contrast to reverse linkage, forward gasification enlarges the combustion space from the bottom to the top and expands laterally between the two bore holes.

As in the LLL experiments in the Powder River Basin, the LERC group (3) obtained an oriented core three inches in diameter in the No. 2 bore hole between points eleven feet above the subject 30 ft. thick coal bed to a point 8 feet below the base of the coal bed. Studies of the core showed preferred permeability and fracture joint trends in a northeast-southwest direction. The average dip of the coal seam in the original test well is 6° - 7° N. 54° E. The depths of the coal bed ranged from 363 to 434 feet. All activity was conducted in the southwest quarter of T. 22 N., R. 81 W., about three miles due south of Hanna townsite.

Several other bore holes were drilled within a few feet of each other. Hole No. 3 was hydrologically fractured using a sand-frac and 16,000 pounds of sand was injected. Several fractures were significantly enlarged and air injection tests showed a five-fold increase in air acceptance with major flow in a southwesterly direction. The coal was ignited in well No. 3 with a propane burner. From that point on for a period of several months air was injected at several other bore holes that permitted reverse as well as forward combustion.

Linkage between nearby bore holes was not a problem wherever reverse burns were involved. Various combinations of switching injection holes to production wells and vice versa were employed with good results. In general, the rate of gas recovery was about one and one half times the air injection rate.

The 30 ft. coal bed had the following composition in terms of weight (dry):

Moisture content	0.00%
Ash	19.62
Sulfur	.49
Hydrogen	4.95
Carbon	59.03
Nitrogen	.79
Oxygen	15.12

After carbonization at about 900° C., 33.9% by weight of the total coal was converted to volatiles.

The typical composition of the produced dry gas was as follows: H_2 - 15.96%, N_2 - 53.18%, CO_2 - 19.22%, CO - 6.33%, and CH_4 - 3.91% plus other minor items. (Average heating value - 130 Btu/scf)

It is important to note at this point that the LERC group concluded (3),

> "The air being lost through the sandstone above the coal as previously described, was not entering the reaction zone during the period" (on p. 4).

Farther along (pp. 4 & 5) they comment that:

> "Gas leakage has been reported in nearly all previous underground gasification operations. Controlling product gas leakage is important since loss of a substantial amount of gas would adversely affect energy recovery efficiency".

and further (p. 5), they report no further loss after September 20, and add:

> "This closed system is encouraging and indicates that the strata above and below the coal plus the water along the edges of the coal gasification region are adequate to contain the gasification reactions. This is important since the possibility of fluid loss to the surface or to surrounding strata was an unanswered question prior to this calculation".

The experiment continued on into 1973 during which time three production wells produced gas evaluated at six billion Btu per month. This quantity and quality of gas would be sufficient to produce about one megawatt of electrical power in an on-site plant.

Additional coring of the area to determine the extent and character of the sweep and recovery efficiency was conducted, but the results are not yet available.

The LERC group has since concluded that they have demonstrated the feasibility of gasifying thick, deep seams of subbituminous coal in-situ. They also believe that the techniques employed here at Hanna would even be better suited to deeper seams in possibly the 1000 ft. range.

Other Domestic In-Situ Experiments

Through this same time interval, since about 1972, other experiments have been conducted (4). The Directed Drilling and the Longwall Generator Process has been conducted by the Morgantown Energy Research group (MERC), in West Virginia, and a Steeply Dipping Bed Process that has been undertaken by Gulf near Rawlins, Wyoming. The results of these experiments will not be available until 1979 or 1980.

Economic Analyses of Production

Although attempts have been made to analyze the economics of the different techniques of in-situ gasification, very little can as yet be accomplished. (See Second Annual Underground Gasification Symposium, Morgantown, West Virginia, Aug. 10-12, 1976, MERC/SP76/3, March 1977). Each of the studies has been based on different assumptions that make comparisons impractical. There are many alternatives to be considered, which involve the processing stages for the final gas product, that create misunderstandings about economic comparisons.

This much can be deduced from the experimentation to date. When coal is gasified using only air, the resultant product is low Btu gas. Such a product can be upgraded through the addition of rich natural gas, or it can be used as a boiler fuel for the generation of electrical power. If oxygen, or combinations of oxygen and steam, are used to gasify the coal, the resultant product is a medium - Btu gas that can be converted to more valuable products such as methane, ammonia, methanol, or other organic chemicals.

In either case, the cost of the final product must be able to compete with the cost of other available materials such as natural gas, petroleum, and strip-mined coal that are also available.

On-going and Future Experiments

It should be obvious that before commercial scale in-situ gasification can be achieved, the entire process and technology will have to be thoroughly tested over an extended period of time. In other words, the entire process will have to prove that it is economically and technically feasible and ready for commercialization. Much consideration will have to be given to the local conditions (geographic, geologic, hydrologic, and atmospheric) at any proposed site.

Additional field tests (4) are now underway by the LERC group at the Hanna site. One experiment is testing the effect of in-situ combustion on the associated ground water. At present 12 monitoring water wells have been positioned around a burn site to provide monthly water samples for analyses. These efforts follow a similar experiment in Czechoslovakia, conducted about 1950, that failed to reveal any significant change in the ground water quality apart from the immediate area of pyrolysis. Similar tests were also conducted by the LLL group at the Hoe Creek site in the Powder River Basin, but the results are difficult to evaluate in terms of significance. They have drawn no specific conclusions as yet.

The field test sequence at Hanna (4) also includes three more experiments in an effort to scale-up additional data for a pilot scale project. The Hanna 3 experiment was a two-hole burn to produce an underground cavity for a more thorough analysis over a longer period of time to determine the effect on ground water quality. The Hanna 4 experiment will be a 3-hole test of process performance with bore hole spacings at 100 and 150 ft. Hanna 5 will be a 9-hole gasification experiment to test the parallel operation of three gasification lines attempting to provide an areal sweep of the coal bed. Design and construction of a pilot scale plant in FY-80 and 81, and tests are planned for FY-82.

Elsewhere, other tests will be conducted (4). The MERC group will be testing several of the techniques on eastern coals, and industry is expected to conduct experiments of the linked-vertical-well process on thicker and deeper western coals and lignites. It has been assumed that if the experimentation is successful, a commercial plant would be near completion in 1985. No decisions have been made yet regarding the size of the plant, but it could be equivalent to a 100 MW electrical power plant according to the concepts of the LERC group. A great deal of additional testing will be required to determine the practicality of operating the production bore holes as modules that can be added, or subtracted, from the operation.

Meanwhile, the LLL group is expected to conduct additional experiments with subsurface explosive fracturing in thicker and deeper coals. These tests have been tentatively scheduled for FY79-81.

Wyoming Concerns for Increased Experimentation and/or Production

Inherent in Wyoming's overall make-up are geological conditions and situations that are desirable for experimentation and possible commercial scale development of low Btu gas produced through underground in-situ gasification. In all probability this work by research and industry groups will continue, and in that event Wyoming's concerns should include at least the following major items.

Land and Mineral Ownership - Throughout most of Wyoming's coal-bearing regions there is adequate federal, or combinations of federal and State land that could be made available for further experimentation and/or commercial development. It would be advantageous if State lands were included and under lease as part of a gasification site, rental payments would be due, and royalty payments would be made as the result of production.

In the event that an experimental or commercial site for gasification is selected adjacent to State lands, the State should request a one mile buffer zone around the perimeter of federal lands to protect the State tract.

Resource Availability - From a practical standpoint any of Wyoming's coals can be gasified. Inasmuch as these coals can be found at practically any depth from the surface down to as much as 9000 ft., sites for underground in-situ gasification are essentially unlimited. The coals range in rank from lignite in the extreme northeast corner of Wyoming's Powder River Basin to bituminous coal in the vicinity of Rock Springs. However, the great bulk of Wyoming coal ranks as subbituminous. The coal occurs in all combinations of individual and multiple beds with individual bed thicknesses ranging up to 220 ft. at Lake DeSmet in Johnson County. Btu content of the Wyoming subbituminous coals ranges from 7000 to 11,000 with general averages around 8500 on an as received basis. Figures of this kind have little significance when applied to in-situ gasification, however, because of the other variables involved with subsurface combustion.

Surface Subsidence - One of the detrimental effects of shallow underground gasification is surface subsidence. In Russia where underground burns have been conducted over several years small scale subsidence has occurred and studies of the effects have been reported (5). For the most part the subsidence was anticipated as a direct result of roof collapse immediately over the burn site.

The degree and extent of subsidence is essentially a function of combustion depth below the surface and the physical character of the overlying strata. In general, the shallower the combustion chamber, the more susceptible an area is to roof collapse and surface subsidence.

Here in Wyoming there is ample evidence of surface subsidence associated with natural underground fires in coal beds that are believed to have been active for several hundred years.

One prime example is the area now known as "Lake DeSmet" in northern Johnson County. In the middle 1800's and recorded in early military reports, and by Father DeSmet, the area was a marsh or swamp. Subsequent coring by Reynolds Aluminum Company across the area and under Lake DeSmet now shows the extent of clinker (burned out coal) that caused the area to subside and become a swamp in the first place. The vertical contact between the unburned coal bed and the clinker coincides with the approximate western shoreline of the original swamp.

In the event that additional underground coal burns are to be conducted in Wyoming, the State should insist that all combustion zones be below 500 ft. as a minimum depth in order to protect the surface from subsidence. The greater the depth the less chance there will be for subsidence to occur. Any large scale, commercial-size, gasification operation should require that all combustion be conducted at least 1000 feet below the surface.

<u>Ground water</u> - With underground temperatures approaching 500 to 600° C during pyrolysis of the coal and the release of volatile constituents, liquids

and tars into the encompassing strata, there will be contamination of ground water locally, in the immediate vicinity of the combustion site. In studies (6) conducted by the U.S. Geological Survey in conjunction with LLL at the Hoe Creek I site in the Powder River Basin, combustion of the coal introduced a broad spectrum of organic constituents into the water that was sampled and analyzed from nearby monitor wells. Although the combustion area at the Hoe Creek site was very small, the water analyses have demonstrated the need for concern because of the presence of phenols and other possibly carcinogenic materials and the possibility that these agents would be introduced into important ground water aquifers of the area.

Although there is no evidence, or real data, to demonstrate that underground coal burns contaminate ground water supplies, every effort should be made to protect Wyoming's aquifers by selecting combustion sites very carefully. It is also important to note that there are probably many water wells in Wyoming used for livestock purposes that were completed in natural burned-out coal and clinker beds that have functioned without serious effects.

In order to protect the quality of Wyoming's ground water from possible contamination during and following underground combustion, all permits for underground gasification should be carefully reviewed and approved by the State Engineer's Office, the Department of Environmental Quality, and possibly the Wyoming Geological Survey. The best protection would be to require that all such programs be carried out at depths of 1000 ft. or more, and even then carefully reviewed by the State agencies.

Other Considerations - It would be in Wyoming's best interest to organize a joint meeting of appropriate State agencies to discuss future underground coal gasification experimentation (or possible commercial scale pilot plants). At present there is no appropriate mechanism in State government to handle such matters. The agencies should develop a method for evaluating future government and industry proposals involving in-situ combustion sites, and have authority to issue or deny appropriate permits with the assurance that other resources and State lands are being protected.

There is also the possibility that other, as yet untried, methods of recovering commercial quantities of low Btu gas from in-situ combustion may be developed and require extensive experimentation. Some thought should be given to whether State agencies would care to enter into joint cooperative projects with the Department of Energy to pursue further experimentation. There would be a distinct advantage in having State representatives involved in any future programs.

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IN-SITU COAL DEVELOPMENT
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