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ASSESSMENT OF IN-SITU COAL GASIFICATION

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# AN ASSESSMENT OF IN SITU COAL GASIFICATION*

H. M. Stoller
Sandia Laboratories
Albuquerque, New Mexico 87115

C. F. Brandenburg
Laramie Energy Research Center
Laramie, Wyoming 82070

and

D. A. Northrop
Sandia Laboratories
Albuquerque, New Mexico 87115

## ABSTRACT

Since 1973, ERDA and its predecessor agencies have been conducting field experiments, laboratory investigations and analytical studies on in situ coal gasification. While the U.S. development of this technology is still in an early stage, a significant amount of information is becoming available by which to assess the technical feasibility, economic viability and environmental impact of this approach to coal resource utilization. This paper will discuss, based on available information, such factors as resource applicability, resource utilization, process products and economics, environmental impact, and health, safety and societal aspects. The overall conclusion is that current results are extremely encouraging and an accelerated development of this technology is warranted.

## INTRODUCTION

The origins of in situ coal gasification are well known: the concept was first proposed by the British in 1868 and subsequently by the Russians in 1888. The Soviet Union, beginning in the 1930's, undertook a large scale program to develop the technology; this program is presumably active today, although on possibly a reduced scale. Recent translations of the voluminous Soviet literature and analyses of this information have provided significant insight into the extent and results of their program.[1-3] Great Britain undertook a modest experimental program after World War II.[4] In the United States, the Bureau of Mines conducted a series of experiments at Gorgas, Alabama in the 1950's[5,6] and Gulf Research conducted a test in 1968.[7] Generally, all programs demonstrated the technical feasibility of in situ coal gasification, but they lacked significant impact as the energy recovery was economically uncompetitive with other energy sources and lacked a sound understanding of the underground phenomena critical to process optimization.

United States interest was rekindled on the basis of an assessment commissioned by the Bureau of Mines in 1971 and due to evidence of an impending energy shortage and increased energy costs.[8] As a result, a series of field experiments were initiated in 1972 by the Laramie Energy Research Center (LERC) at a site near Hanna, Wyoming. Three tests have been conducted to date with significantly encouraging results as summarized in Table 1; additional tests are scheduled.[9-12] With the formation of ERDA, an overall program for underground coal gasification was formulated.[13] Projects were initiated in four different processes for in situ coal gasification: (1) the linked vertical well process being conducted by LERC at Hanna and which has been the most extensively tested;

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(2) the packed bed reactor concept proposed by Lawrence Livermore Laboratory in which explosive fracturing experiments and a preliminary gasification test have been conducted; (3) the longwall generator concept being pursued by the Morgantown Energy Research Center in which a deviated well has been drilled and a first field test has been scheduled; and (4) a concept for steeply-dipping seams will be initiated this year by ERDA. Further, Sandia Laboratories, in collaboration with LERC, is investigating the development and application of instrumentation techniques to the monitoring and control of in situ coal gasification.[13] Under private industry funding, the Texas Utilities Service Company has licensed the Soviet in situ coal gasification technology and have conducted tests in Texas lignite deposits.[13]

Table I

The Hanna In Situ Coal Gasification Experiments

| | | Air Injection MM scf/day | Gas Production MM scf/day | Heating Value Btu/scf | Potential Power MWe |
|---|---|---|---|---|---|
| Hanna I | 1973-74 | 1.1 | 1.6 | 126 | 0.9 |
| Hanna II, Phase 1 | 1975 | 1.9 | 2.7 | 152 | 1.7 |
| Hanna II, Phase 2 | 1976 | 5.0 | 8.6 | 180 | 6.3 |

In reality, this fresh look by the United States at an old technology is still in an early stage. The undertaking is a difficult one, especially considering the complexity of conducting processes in an inaccessible in situ environment where nature controls many of the important parameters and where variability is the rule. It is appropriate, however, to attempt an assessment of in situ coal gasification based on the progress, experience, and knowledge to date. The objective of this paper is to present an individual perspective as to where the state-of-the-art presently stands with respect to the potential and problems of in situ coal gasification.

## POTENTIAL AND PROBLEMS

The dominant reason behind the interest in in situ coal gasification is the vast extent of the coal resources in the United States which are currently estimated at 3.9 trillion tons of which 1.73 trillion tons occurs at depths between 0 and 3,000 ft.[14] This interest is enhanced when it is learned that approximately 10-15 percent of this 3.9 trillion ton resource can be economically mined by current technology for reasons of the coal deposits being too thin, too thick, too deep, or too water-saturated. The remaining 85-90 percent, then, is the target of in situ coal gasification.

The ultimate objectives of developing this technology are to expand this nation's supply of economically recoverable energy and to efficiently transform the coal resource into more available and useful forms.

Major advantages have been postulated for in situ coal gasification in several categories: (1) resource utilization - as discussed above and an increased percentage of coal extracted relative to underground mining; (2) thermal efficiency - recovery of nearly 90 percent of the energy of the coal affected has been demonstrated; (3) product utilization - a wide variety of product options are potentially available based upon the gasification concept and energy demands; (4) environmental - the reduction of atmospheric pollution and lessened surface disruption relative to strip mining; (5) economic - a lower capital investment and competitive economic estimates; and (6) health, safety and socio-economics - a reduced impact as miners and mining are not required and fewer labor-intensive activities are involved.

Equally important, a number of potential problem areas have been hypothesized. These include: (1) the efficiency of overall resource recovery, particularly on a large scale, is unknown; (2) the applicability of in situ gasification to all the "too thin," "too thick," "too deep," or "too wet" coals and some coal ranks is unproven; (3) the effects of subsidence upon the process and the environment have not been determined and its control would be a very difficult task; (4) there are unanswered environmental questions such as groundwater pollution, disruption of aquifers by subsidence, etc.; and (5) demonstration of the variety of product options and product utilization has not yet been achieved.

Note that many of the postulated advantages and problem areas are one and the same. This is not surprising considering the present status of the different projects in addressing technical feasibility, the fact that environmental studies have only been recently initiated, and the limited data base on which to conduct economic and systems analyses. Subsequent discussion will be directed at summarizing available information on these topics.

## Resource Utilization

Conceptually, in situ coal gasification can be applied to all coal ranks and deposits. However, the Soviets and Americans have had their most extensive and successful experience with lignites and sub-bituminous coals. These coals have lower heat contents but have higher reactivity and, more importantly, actually shrink upon heating thus developing an increasing permeability during processing. Experience in bituminous coals has been less encouraging: the experiments at Kamenskaya were not developed as extensively as other Soviet stations and the Gorgas, Alabama tests suffered from plugging, gas losses, and poor and variable gas quality.

The Soviet experience, also seen in the British experiments, indicate that there is an effective minimum seam thickness (in the lower rank coals) of approximately 2 m. Below this thickness, heat losses to the surrounding formations become a significant percentage of the total energy balance resulting in a decreased heating value for the product gas. Conversely, there does not appear to be an upper limit on seam thickness nor on the dip of the coal seam; a seam of 90° dip can essentially be considered a seam of infinite thickness. The Hanna tests were conducted in a 30 ft. seam, seams to 60 ft. thickness were utilized at Angrenskaya, and at Yuzhno-Abinskaya twenty-three seams of 4 to 12 ft. individual thickness at dips of 55-70° were extensively gasified. The important factor is that gasification be initiated near the bottom of the seam so that the reaction front initially undercuts the coal; coal subsequently caves into the void and thus increases the reaction surface area, maintains permeability and results in increased resource utilization.

Experience also suggests that there is an upper limit on allowable water intrusion into the reaction. Some water is required to increase the product gas heating value (by the reaction $H_2O + C \rightarrow CO + H_2$). Too much water can: (1) cool the gas, producing a less desirable equilibrium composition; (2) promote the water gas shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$) diluting the heating content of the product gas; (3) effectively quench the combustion reaction if intrusion rates are very high; and (4) presumably disrupt gas flow distributions within the seam.

Technologically, depth does not appear to limit gasification. However, practical well completion factors, higher injection and operating pressures, and economic considerations must be addressed. The Soviet work at Lisichanskaya was conducted at depths of 1,000 ft. LLL's packed bed reactor concept is aimed at thick seams at depths greater than 500 ft., so operation at higher pressures would promote the production of methane.

A very real dilemma is posed in the utilization of the extensive bituminous coal seams of the Eastern United States as summarized in Table II. As seen by the preceding arguments, thin, often deep, seams of swelling bituminous coal are less amenable to gasification. However, the bituminous coals are located where the greatest population and resulting energy demands exist at this time. Thus, emphasis needs to be applied to developing in situ processes which can exploit these resources to satisfy these demands. MERC's longwall generator concept is aimed at these eastern coals but it has not yet had its first field test. Thus, it is difficult to assess the degree of success to be encountered in these resources.

Table II

The Eastern "Dilemma" for In Situ Coal Gasification

| Western Region | Eastern Region |
| --- | --- |
| Thicker Seams | Thinner Seams |
| Non-Swelling Coals | Swelling Coals |
| Lower Rank and Sulfur Coals | Higher Rank and Sulfur Coals |
| Air Blown, Electricity Product is the Field Demonstrated Concept Closest to Commercialization | Greater Population with Critical Energy Demands |

Requires: Alternative, "Shippable" Products from Western Coals
Investigation of Concepts for Eastern Coals

A final discussion on resource utilization concerns the fraction of coal in place which is actually recovered. Underground mining typically leaves 50-65% of the original coal in place in columns to prevent subsidence and maintain mine integrity. In a developed field, the Soviets frequently obtained, by in situ gasification, better than 80% and often approaching 100% utilization of the coal contained within a tract. In the recently completed Hanna test, 4600 tons of coal were contained in the 30 ft. thick seam within a 60 x 60 ft. well pattern. In situ instrumentation indicated that the entire seam thickness was gasified and a total of 6700 tons was ultimately gasified indicating outstanding resource utilization for this particular test.

Process Efficiency

Care needs to be taken when discussing efficiencies associated with in situ coal gasification: specific definitions are required, especially if comparisons with other concepts or energy technologies are desired.[15]

At a minimum, a process must produce more energy than is invested in its production. For recent Hanna tests this ratio* was approximately 4.5 - 5.3. These tests used diesel-powered air compressors to supply air for gasification; by utilizing more efficient air compressors, even providing for the electrical power demands of the site, it is believed that this ratio can be raised to 8 and possibly higher.

Thermal or chemical efficiency can be defined as the ratio of total usable energy produced by the process to the total energy available in the amount of coal gasified. In the Soviet experience, efficiencies achieved were typically 45-65%. The lower values corresponded to the deleterious effects of too much water intrusion, thinner seams and loss of the produced gas by leakage caused by subsidence. The same ratios observed for the recently completed Hanna II tests were 76-89%; the lower value is for a portion of the test when increased water intrusion was noted. While the high values for thermal efficiencies are encouraging, their variability emphasizes the need to test in situ processes in different coals and locations before their widespread applicability is proven.

*The ratio of the heats of combustion of the dry product gas and liquid by-products to the energy consumed in operating the process.

In terms of the efficiency for an overall process, the energy required to operate the process (compressors and site utilities) would be added to the denominator. This results in an overall process efficiency defined by:

Heating Value of Dry Product Gas
+ Heating Value of Liquid By-Products
+ Latent and Sensible Heat of Water Vapor
+ Sensible Heat of Dry Product Gas
divided by
Energy Available in Coal Consumed
+ Energy Used to Run Process

Values of 76-80% for this ratio were obtained for the Hanna II tests.[15]

Finally, the fraction of the total coal recovered (80 to 100%) and the efficiency of the surface conversion to the final product (e.g., 33 to 45% for electricity) would have to be considered in determining an overall product utilization efficiency. In any case, the recent tests have demonstrated clearly attractive and competitive efficiencies.

Product Utilization

One of the attractive features of in situ coal gasification is the number of product options which appear possible. These are summarized in Figure 1.

Airblown gasification, which produces a low heating value gas (120 - 180 Btu/scf), for electrical power generation has been the most extensively investigated and is the option closest to commercial utilization. This low Btu gas, because of its nitrogen content, could also be utilized in the production of ammonia.

The Russians conducted limited experiments with oxygen-enriched air as a means of increasing the heating value of the gas. A 65% oxygen enrichment of the air-blown gasification process doubled the heating value of the product gas, but this gain was not economically satisfactory and enrichment was not commercially pursued by the Soviets.

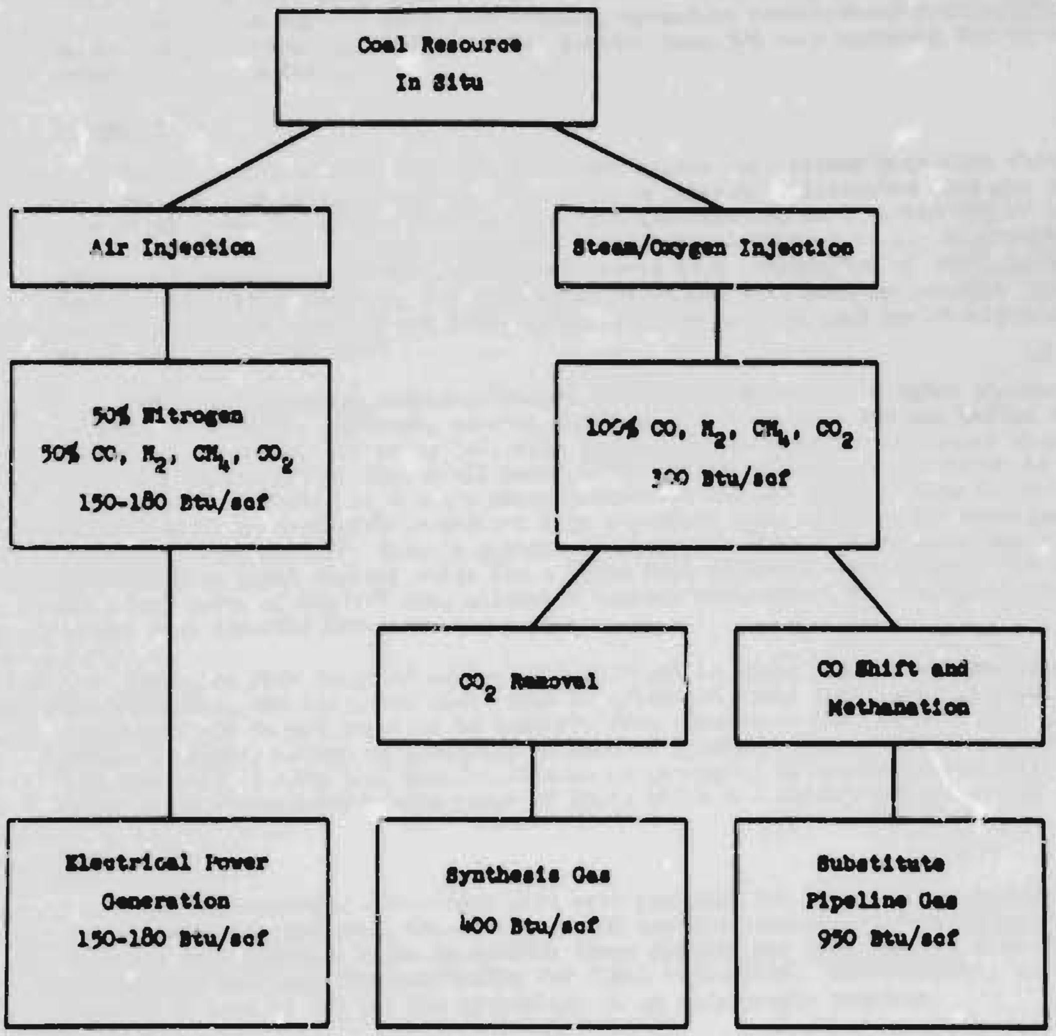
Steam/oxygen injection has not been field tested to date and its feasibility is based upon analytical studies and laboratory experiments. It is attractive from the standpoint of producing a nitrogen-free hydrocarbon product gas which could be upgraded to methane (substitute pipeline gas), be utilized for process heat, or be employed as a feedstock for a variety of petrochemical processes. However, until steam/oxygen field tests are performed or ways of removing nitrogen from an air-blown product gas are developed, the right-hand options in Figure 1 must remain a promise.

This promise, however, has led to several studies which have proposed the utilization of the intermediate heating value gas ( ~ 300 Btu/scf, nitrogen free) as a synthesis gas or chemical feedstock for fertilizer, methanol, or other petrochemical products, as a reducing agent for iron ore and other processes, and for a source of process heat for industrial applications. As the reforming of natural gas is a major source of synthesis gas in today's industry, the development of an in situ coal gasification technology, for these industrial applications would have double impact in alleviating present energy shortages.

The upgrading of intermediate heating value gas by the shift reaction and subsequent methanation to produce methane, (i.e., a substitute pipeline or natural gas), has received major attention in surface gasification processes. A number of surface demonstration plants are being pursued by ERDA. Over 20 commercial-size plants based upon Lurgi technology have been proposed by industry, but none have been built to date. The capital demands (now estimated at over $1 billion per plant), large cooling water requirements, the need for supporting mines, and gasifier construction (which, on the projected scale, will severely tax this nation's fabrication capability for these larger pressure vessels) have delayed their development. In situ coal gasification offers the potential to essentially eliminate many of these deterrents as the in situ process would serve as a substitute for the first step in the gasification of coal to produce a high Btu product.

Figure 1

PRODUCT OPTIONS FOR UNDERGROUND COAL GASIFICATION



The Soviets have utilized the low Btu gas from air-blown gasification to generate electricity. Total gas production at Angrenskaya for 1963 ($31 \times 10^9$ scf of ~100 Btu/scf gas, some 2/3 of the Soviet in situ coal gasification production) was sufficient to produce more than 30 MWe of power. In comparison, for two one-month long periods the most recent Hanna experiment produced gas at rates sufficient to generate 6.5 MWe;[8] however, the gas was flared and not utilized.

Present United States development has focused upon the underground reaction and demonstration of coal utilization and acceptable gas production. Once demonstrated, gas-fired turbines, or steam power plants could be utilized for electrical power generation at the site. Advanced power systems for surface low Btu gasification now under development may also find application. In situ gasification may, however, have some unique problems in electricity generation and appropriate measurements are being made in conjunction with the field experiments. Such problems as particulate scrubbing, potential pollutants and gas product fluctuations have been addressed in one study.[16] Utilizing a typical gas mixture from the Hanna I test (126 Btu/scf), various Rankine, Brayton and combined power generations cycles have been analyzed. Dependence of cycle efficiencies upon turbine inlet temperature, operating pressure and configurations were determined; combined cycle efficiencies greater than 50% were obtained for several conceptual system designs.

Economics

The limited technical data of the United States' experience precludes absolute cost studies from being conducted. The Russian literature indicates that gas costs for electrical power production from in situ coal gasification were within 50% of being economically competitive with production from strip-mined coal (e.g., Angrenskaya, 1963: 20.1 roubles/ton of coal equivalent versus 14.2 roubles/ton of strip-mined coal).[2] Soviet predictions, however, for full capacity plants were more optimistic: projected electricity costs were 1.3 and 2.26 kopecks/kWh for in situ coal gasification and strip-mined coal, respectively.[2]

Soviet and American economics cannot be directly compared so these arguments cannot be extended further. However, several analyses have been made for the United States resources, concepts, and economics, with the end products being considered either substitute pipeline gas or electrical power.[17-23] These results are tabulated in Table III. Another study directed at on-site power generation did not believe that electrical plant designs could be sufficiently defined from available data to allow for detailed cost estimates to be made.[16] Thus, a parametric study of process performance was performed and allowable plant capital costs for a given fuel price was determined. For example, with fuel costs of 80¢/$10^6$ Btu, allowable capital investments for different power cycles ranged from 230-280$/kW.

Given the wide range of assumptions utilized in these studies and the inherent uncertainties, the resulting wide range in estimated costs that were obtained is understandable. It is not possible to conclude from these data that in situ coal gasification offers a cheaper method of producing methane or electrical power. However, studies do indicate that in situ coal gasification-based processes do appear economically competitive given today's wide range of costs which are encountered in energy production.

Environmental

Many environmental advantages have been promoted for in situ coal gasification. At the same time, however, the environmental aspects remain one of its largest unknowns. Work has only recently begun to address these aspects and will require several large-scale tests and long-term monitoring for final evaluation. Nevertheless, results and studies to date do not put the technology in an unfavorable position.

Table III

Various Economic Comparisons

| Synthetic Pipeline Gas ($/MSCF) | Ref. | In Situ | Surface Gasification | Conventional |
|---|---|---|---|---|
| Western, LLL Process, Optimistic | 17 | 1.95 | 2.85 | -- |
| Western, LLL Process, Conservative | 17 | 2.83 | 2.85 | -- |
| Western, LLL Process | 18 | 1.73 | 3.02 | -- |
| Western, LERC Process, Conservative | 19 | 3.52 | 4.62 | -- |
| Eastern, MERC Process, Conservative | 19 | 5.02 | 5.56 | -- |
| Midwest, Gulf Process | 20 | 2.21 | 2.98 | -- |
| Western, Gulf Process | 21 | 1.57 | 2.49 | -- |
| Eastern, Gulf Process | 21 | 2.28 | ?.45 | -- |
| **Electrical Power (mils/kW-HR)** | | | | |
| Western, LERC Process, Busbar Cost | 22 | 7.5 | ---- | 17.2 |
| Western, LERC Process, Conservative | 19 | 35.4 | 39.2 | 28.3 |
| Eastern, MERC Process, Conservative | 19 | 49.1 | 44.7 | 32.6 |
| Western, LERC Process | 23 | 8.4 | 17.2-20.9 | 8.9-11.1 |
| Eastern, MERC Process | 23 | 18.2 | 20.5-23.0 | 12.7-14.3 |

In situ processing will obviously produce less surface disruption than will strip mining of the same resource. However, removal of the coal over an extended area will cause subsidence. Subsidence effects will be site-specific and determined by the geology and extent of coal removed. The Russians have noted subsidence in their tests with deleterious effects upon the process itself and with some gas leakage to the surface.

However, in the western states, much of the strippable coal is underlain by coal seams appropriate for UCG, thus, gasification could take place before reclamation and increase the total energy extraction per dollar of reclamation.

It is not known in this country whether subsidence will have to be controlled (i.e., minimized or eliminated) or whether it can be allowed to occur, hopefully in a predictable manner. It is estimated that a 1000 MWe plant, operating for 20 years by the gasification of a 50 ft. sub-bituminous coal seam would require less than four square miles of surface area, and would produce subsidence of approximately 15 ft. over that area. This subsidence and the associated drilling and production facilities would be the extent of the surface disruption. It should be reemphasized that United States' tests to date have not been conducted on a scale sufficient to cause observable subsidence at the surface.

Potential water problems come from the pollution or disruption of aquifers. Most coal deposits are more permeable than their surrounding formations and, thus, when subsurface water is present, tend to be aquifers. Gasification of coal in this aquifer utilizes some of the water. Soluble (phenols, etc.) and insoluble (tars, etc.) organic products are produced which can be transported into the aquifer. Finally, the "activated" ash and temperatures associated with the gasification process result in increased solubility of inorganic materials. Several mitigating factors with respect to possible aquifer pollution exist. Groundwater movement is slow and can be of the order of a meter a year. Another study indicates that the remaining coal outside the gasified region acts as an adsorbent for organic pollutants and, while not as effective as activated charcoal, it does have a similar capacity.[24] These factors would sharply restrict a pollution zone to close to the process boundaries, even for considerable lengths of time. Roof collapse and subsequent subsidence could disrupt overlying aquifers and affect their use. While these are site and geology specific, most major aquifers tapped for use lie well below the coal deposits considered for gasification. LERC is presently conducting a small scale test specifically aimed at the investigation of hydrological and environmental interactions with an in situ coal gasification process.

The extent of air pollution effects will, of course, depend upon the final product utilization, but real promise exists compared with mined-coal-fired electrical generation plants. Tests at Hanna show that only about one-tenth of the coals' 0.7% sulfur content comes to the surface in the product gas; the balance presumably remains underground as inorganic sulfides. Furthermore, the sulfur in the product gas appears as $H_2S$ which is more amenable to established scrubbing procedures than is $SO_2$ - the end form of most of the sulfur in air-fired, surface coal combustion processes. Quantities of fly ash in the product gas at the Hanna tests were quite variable, but it appears that adequate design and low space velocities can leave essentially all of this pollutant underground. This may also result in economic advantages as fly ash scrubbing and removal by electrostatic precipitators to meet state and federal standards are a major cost item in surface generating plants today.

Health, Safety and Socio-Economic Impact

No definite studies of these aspects of in situ coal gasification have been conducted so that extensive discussion is not warranted. Previous sections have touched upon potential advantages, such as the elimination of mining and its associated hazards, the fact that high pressure and toxic "reactors" remain underground, and that a less labor-intensive industry due to the reduced construction and size of the operating plant will be required.

## CONCLUSION

The technical feasibility of in situ coal gasification has been demonstrated in several field experiments throughout the world. Today's increased energy demands, the escalating costs of crude oil and natural gas and the success of recent small-scale field experiments lends support to the belief that this technology could offer an attractive near-term alternative to increasing this nation's energy supplies. Hence its development should be vigorously pursued to develop the data to obtain a comprehensive assessment.

Potential advantages include resource utilization, thermal efficiency, product utilization, reduced environmental and socio-economic impact, and process economics. Similarly, potential problem areas, or more correctly process related unknowns, may exist with respect to overall resource recovery and widespread applicability to all coal resources, the environmental effects of subsidence and water quality, and the demonstration of the viability of the different product options. The similarity of the postulated advantages and the unknowns are characteristic of the present status of the technology.

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