PROBLEMS SOLVED AND PROBLEMS NOT SOLVED IN UCG

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INTRODUCTION

Several different processes of UCG (Underground Coal Gasification) are being investigated in North America. Of these, the linked vertical well process, developed by the Laramie Energy Research Center, has been field tested most extensively and is closest to eventual commercialization. There is, consequently, substantial participation in further field testing of the linked vertical well process or minor variations of it. Partial or complete industrial participation is involved in the field testing programs of the Alberta Research Council, Texas A&M University, and Texas Utilities.

Problems, some solved and some not solved, which are associated with UCG are discussed in this work. Discussion of these problems outlines the current status of the linked vertical well process. The purpose is to provide perspective concerning what has been accomplished already and what remains yet to be done on the road to commercialization of UCG.

PROBLEMS SOLVED

1. Low Gas Quality

An appraisal of world-wide research efforts in UCG through 1971 showed that no field experiments using air injection had consistently produced gas with a heating value of more than 4.7 - 5.1 MJ/m^3 (120-130 Btu/scf). In most cases the gas heating values averaged less than 3.9 MJ/m^3 (100 Btu/scf) (1). In contrast all experiments conducted at Hanna, Wyoming, have resulted in heating values above 4.7 MJ/m^3 (120 Btu/scf). During the best controlled of all of the Hanna experiments, the Phase II Hanna II test, the gas heating value averaged 6.7 MJ/m^3 (171 Btu/scf) at production rates exceeding 215,000 m^3/day (8 million scf/day).

The favorable results at Hanna stem from three well defined conditions:

1. Favorable geological conditions (2, 3). An impervious shale overlies the Hanna No. 1 coal seam. The seam is relatively thick, 9 m. It lies at sufficient depth, 82-122 m, so that gas leakage to the surface has not occurred. A single aquifer, of very low productivity, overlies the coal seam.

2. Subbituminous coal. Mathematical model calculations show that the heating value of gas produced from either lignite or bituminous coal should be lower than the heating value of gas from subbituminous coal. Gases produced by carbonization of the coal make up a substantial part of the fuel gases produced by UCG. Subbituminous coal has a high volatile content; in addition, the carbonization gases are rich in methane.

In boreholes and large channels, probably the most critical chemical reaction is the steam-carbon reaction

$$C + H_2O \longrightarrow CO + H_2$$

which requires a long residence time compared to simple combustion. In an open borehole, or a borehole partially filled with rubble and large pieces of coal, there is poor contact between the solid coal char and the mixture of water vapor and hot combustion gases.

In contrast in the linked vertical well process, no open borehole exists between the air injection and gas production wells. Instead gases permeate through the dried, partially devolatilized coal. Average particle size, at least for the Hanna No. 1 Seam, is on the order of one millimeter. Because there is intimate contact between gases and solid, the gasification reactions are more extensive; and gas heating values, consequently, are higher. Bituminous coal contains less volatile matter and, therefore, produces a lower heating value gas. Lignite has a high volatile content, but on devolatilization relatively little methane is produced and a lower quality gas is obtained.

3. Control of water influx. Soviet data from field tests and commercial operations (4, 5), mathematical model calculations (6, 7, 8), and experimental results from Hanna, Wyoming, (9, 10) all verify that a too high water influx can produce a major deterioration of gas quality. The physical reasons for the deleterious effect of water have been discussed elsewhere (5, 6, 8, 10). Most western Tertiary coal seams are aquifers. The Hanna No. 1 coal seam, however, is a relatively unproductive aquifer. Therefore, it is relatively easy to adjust air injection rates to maintain a near optimum air/water ratio.

2. Decreasing Heating Value

In many field tests the gas produced started initially with a reasonable heating value which then declined gradually to unacceptable values. Two mechanisms are known which can cause this behavior:

1. Use of boreholes. One method of coal gasification involves the drilling of boreholes to connect the injection and the production well. The coal is ignited then and gasified along the length of the borehole. In this process the coal burns radially outward, and the borehole increases in size. As the borehole grows in size, more gas by-passes the coal; and the gas heating value deteriorates correspondingly.

2. Higher water influx for larger burned areas. Since many coal beds in the West are aquifers, water influx tends to increase as more and more surface is exposed by the combustion front. In addition, for larger burned out areas subsidence occurs establishing communication with overlying aquifers within the subsidence zone.

With an exception discussed later in this paper, a drastic decline in gas heating value has not occurred during the Hanna field tests. The major reason is that the linked vertical well process used at Hanna is not a borehole method but a permeation method, that is, it is essentially a packed bed process. Packed beds are widely used in the chemical process industries. A principle, well known among process chemists and engineers, is that for satisfactory results channeling must be avoided in packed bed equipment such as chemical reactors, liquid-liquid extraction columns, and distillation towers. None of the Hanna field tests have yielded any definite evidence that open channels have been created.

Thermal data from instrumented observation wells (11), flow rate and gas composition measurements (9, 12), and mathematical modeling (6, 7) have been used extensively in developing the foregoing description of the mechanics of the linked vertical well process. As more is learned about the process, it becomes increasingly clear that lignite and subbituminous coal properties are especially amenable to UCG. Both types of coal shrink on heating, and drying alone increases the coal permeability by about two orders of magnitude (13). It is these properties which permit reverse combustion linking and a permeation type gasification process to be used.

3. Variability in Gas Quality and Gas Production Rates

A wide variability in gas quality and production rates has been observed on an hourly or daily basis in many field experiments. The need for a constant gas flow rate, however, presents no real problem. It is readily achieved with a constant air injection rate and with the use of a flow control valve on the production line.

At Hanna variations in gas heating values on the order of $\pm$ 5 to 10 percent have been observed at a single well on a daily basis. This falls within the acceptable limits for the firing of large boilers. For a commercial operation, however, many production wells would be in use simultaneously and the variability in the gas composition would tend to average out. It is also noted that gas variability has been more extreme in the borehole or streaming methods of UCG.

4. Low Thermal (Cold Gas) Efficiency

In this work thermal efficiency is defined as the upper heating value of dry gas and liquids produced divided by the heating value of the coal consumed. Consistent with this definition, sensible heat is not included nor is the latent heat of any water vapor in the gas.

The instrumentation used during the Hanna field tests permits a accurate determination of the thermal efficiency. These efficiencies are the highest ever recorded. The Phase II Hanna II test achieved an

efficiency of 89 percent for the entire 25 days of the test during which 2300 tonnes (2500 tons) of coal were consumed.

Such high efficiencies are readily achieved under good operating conditions. The many feet of earth overlying and underlying the coal seam provide excellent insulation. In thick coal seams, therefore, the UCG process operates nearly adiabatically. Most of the thermal energy released from the combustion of coal char and air must be produced at the surface in the form of sensible and latent heat and in the heating value of the gas produced, i.e., chemical heat. The sensible heat is a less convenient form of energy because it can be transported only over very short distances.

In the borehole or streaming method of UCG a substantial portion of the hot combustion gases by-pass the coal and a considerable portion of the total energy released appears at the surface in the form of sensible heat. In permeation processes only a small portion of the energy goes into sensible heat. The combustion gases intimately contact the coal, and most of the sensible heat is used up for the highly endothermic steam-char reaction which produces a combustible gas.

A number of conditions can lead to lower thermal efficiencies as well as lower gas heating values.

1. Thin coal seams. A larger portion of the energy is lost to the surrounding rock formations.

2. Very high ash coal (over 50 percent). A substantial portion of the thermal energy is taken up by the ash.

3. Low air injection rates. Gas residence time underground is longer, and a larger portion of the energy is lost to the surroundings. Very low air flow rates also result in lower reaction zone temperatures.

4. Gas channeling. This results in poor contact between gases and coal.

5. Too high water influx. Vaporization of the water uses up much of the available thermal energy.

6. Gas leakage.

The mathematical model mentioned in this paper can be used to quantify individual effects listed above. It can also be used to quantify the synergistic influence of two or more of these effects acting simultaneously. More detailed discussions of the distribution of energy during the UCG process have been reported for the Hanna field tests (5, 6, 7, 10).

5. Low Resource Recovery

In the borehole or streaming method of UCG, the combustion front tends to travel down the borehole rather rapidly and to break through to the production well. Once this occurs the gas quality deteriorates very rapidly below acceptable levels. Under these circumstances, a large portion of the

coal is likely to be by-passed, and energy recovery is low. In all tests of the linked vertical well process at Hanna, Wyoming, the combustion zone advanced along a broad front, and most of the coal in place was consumed. For example, Figure 1 shows the well layout for Phases II and III of the Hanna II experiment. Wells 5, 6, 7, and 8 are production and air injection wells. Letters A to O indicate instrumented observation wells with thermocouples at several levels within the coal seam. With the thermal data it is possible to track the progress of the combustion zone. These data show that the combustion front burned through all wells within the 60 foot square pattern except well K. It is concluded, therefore, that the areal sweep efficiency is well over 80 percent.

The square well pattern shown in Figure 1 contained 4170 tonnes (4600 tons) of coal. Material balance calculations based on the carbon content of produced gases show that about 6070 tonnes (6690 tons) of coal were consumed (9, 14). Obviously considerable burning occurred outside the square pattern. In fact, the combustion zone burned through to well A but not to well N on the opposite side of the pattern. At the same time cores of coal taken near burned out regions have shown no real evidence of partial utilization of coal, i.e., cored coal samples indicate no substantial carbonization (15). It is inferred, therefore, that practically all coal contacted by the combustion front is completely gasified.

A two dimensional mathematical model developed for UCG shows reasonable agreement with field performance determined by thermal measurements and material balance calculations (16). When work on this model is completed, it will be possible to predict the shape of the combustion zone for any given well pattern.

6. Overall Process Efficiency

The overall process efficiency is defined here as the upper heating value of dry gas and liquids produced divided by the heating value of the coal consumed plus all energy consumed on site for gas compression, utilities, etc. All tests with the linked vertical well process at Hanna, Wyoming, have shown that UCG is an efficient method of energy recovery (10). Typically about 14 percent of the energy produced is consumed for gas compression and other purposes. Most of the energy consumption is for gas compression. Therefore, the 14 percent figure can be greatly reduced by optimizing the size of well casing and surface piping and utilizing efficient air compression equipment. Pressure measurements show that for a well spacing of 18 m (60 feet), pressure losses are only 0.7-2.0 N/m^2 (1-3 psi) even at air injection rates of 120,000 m^3/day (4.5 million scf/day). Thus, very little energy is lost in forcing air through the coal seam because of the great permeability of lignite and subbituminous coal after drying and devolatilization by reverse combustion. Overall process efficiencies range from 65 to 74 percent for the linked vertical well tests conducted at Hanna, Wyoming (10).

7. Control of Combustion Front

In a permeation type method of UCG such as the linked vertical well process, control of the direction and rate of progress of the combustion

front is achieved through selection of the pattern for production and injection wells and through control of the air injection rate. A two dimensional mathematical model described by Jennings et al. (10) has been used to predict location and shape of the combustion zone with satisfactory accuracy. The theory requires further verification with multiwell patterns.

8. Equipment Reliability

Equipment failures have severely plagued research on surface coal gasification processes. This has not been true with UCG (19). The high level of equipment dependability in UCG results from two conditions, the great simplicity of the surface installations required and the relatively low temperatures of gases produced.

9. Lack of Predictability

A frequent complaint has been that UCG is highly unpredictable; therefore, reliable engineering design was not possible presenting a major obstacle to commercialization of in situ coal gasification. In the past this has undoubtedly been true, but the results from the latest test at Hanna strongly indicate that the problem is close to solution.

Although UCG is not yet ready for commercialization, that time is approaching rapidly. At the present, understanding of the physical and chemical mechanisms controlling UCG is far more complete than of many competing coal gasification processes. This greatly increased understanding has resulted from three developments: extensive instrumentation of field experiments, availability of computers large and small (20), and the development of sophisticated models capable of predicting accurately field test performance.

10. Site Specificity

The very favorable results obtained from UCG field tests at Hanna, Wyoming, have not been duplicated anywhere else in the world. It might be concluded that success is specific to the Hanna site. This is not the case, however. Most of the parameters essential to successful UCG have been identified through the use of mathematical models and of massive amounts of data acquired during four years of field testing. Undoubtedly a number of favorable factors have contributed greatly to successful tests at Hanna, Wyoming; several of these factors have been discussed already (refer to item 1. Low Gas Quality). These factors, however, are by no means unique to the Hanna coal field but occur in many if not most areas of the West.

PROBLEMS NOT SOLVED

No attempt is made here to discuss all research problems which remain unsolved because, even with proven processes, new problems frequently arise. Instead problems which remain unsolved are classified as one of three types as a basis for discussion.

Critical problems. These are problems which, if not resolved favorably, will have a major harmful impact on the commercialization of UCG. Only two problems of this type are known, subsidence and excessive water influx.

Non-critical problems. These are problems which can have a major economic impact, but which will not prevent commercialization even if no favorable solution is found. Uncertainty concerning maximum well spacing is such a problem.

Developmental problems. These are problems which require application of off-the-shelf technology, or are problems which may require new technology but will not have a major economic impact on the process. Gas clean-up is such a problem.

11. Subsidence

Subsidence is probably the most important single obstacle to commercialization of UCG. Because of fiscal limitations, the tests at Hanna have been limited to two and four well patterns with 60 foot spacing. With this spacing no subsidence has been observed at the surface, although subsurface caving of the roof has occurred directly over areas of burned out coal.

When larger UCG patterns are used, subsidence of the surface will occur inevitably. At many locations in the western states this is not an insurmountable problem. Even with extensive subsidence, the surface is less disturbed than it would be by strip mining.

There are, however, three major problems associated with subsidence:

1. Disruption of overlying aquifers. A very sensitive political issue in arid regions.

2. Establishment of communication with overlying aquifers through subsidence and consequent flooding of the combustion zone.

3. Gas leakage to aquifers and possibly to the surface.

Only future field tests with large patterns can determine to what extent the foregoing harmful effects can be minimized.

Of course, if the effects of subsidence should prove intolerable in a given situation, it could be avoided entirely by utilizing small isolated burn patterns. This would be practical only if the rock overburden had sufficient structural strength as it does at Hanna. It would result also in an unfortunate reduction in the amount of recoverable coal.

12. Excessive Water Influx

Virgin coal in the Hanna No. 1 seam has low permeability and is a very unproductive aquifer. For this reason, it is possible to maintain a nearly optimum water/air ratio (moles water produced from the coal seam/moles air

injected) at reasonable air injection rates. This was true for Phases I and II of the Hanna II experiment. Both of these tests involved only two wells spaced 16 m apart for Phase I and 18 m apart for Phase II.

Both the heating value of gas produced and the thermal efficiency of the process were much lower for Phase III than for the previous two tests. Field data (9, 10) and calculations with the mathematical model (8) both confirmed that the deteriorating results obtained in the Phase III test resulted from an excessive influx of water. Physical limitations of the air injection system prevented adjustment of the water/air ratio.

Phase III involved a four well test pattern. Thus, the reaction zone was exposed to a much larger area of water drainage from the coal seam. Also the larger burn area may have promoted greater caving of the roof and communication with an overlying aquifer.

Excessive water influx can be controlled in four ways:

1. Use of dewatering wells.

2. Careful pressure control.

3. Adjustment of the air injection rate.

4. Gasification in an up dip direction.

The degree of success that can be achieved with these control measures can only be proven with the use of large well patterns in future tests.

13. Maximum Well Spacing and Depth

Factors affecting maximum well spacing and depth are largely conjectural and have not been investigated in field tests. Maximum depth at which the process is workable is an important indicator of the amount of coal that may be suitable for UCG. Maximum well spacing is important because the drilling and completion of wells is a major cost item in the operation of a UCG project. Neither is a critical problem, however. There are vast deposits of coal available at depths already tested successfully with UCG. Economic studies indicate that UCG even with the close spacing used at Hanna, Wyoming, may be competitive already with some intrastate natural gas prices (21).

14. Bituminous Coal

It has been emphasized earlier that the linked vertical well process is a permeation method and that this fact has been responsible for much of the success of the Hanna tests. Lignite and subbituminous coal shrink on drying and carbonization. This permits the use of reverse combustion linking, and the establishment of a permeation process during forward gasification. At this time it is not certain that the linked vertical well process can be used successfully in eastern bituminous coal which swells on heating. Because of the large population of the eastern states, it is important to test the viability of UCG in eastern coal. However, this is not classed as

a critical problem, that is, a problem critical to commercialization of UCG. Regardless of the outcome of eastern tests, UCG remains a workable process in lignite and subbituminous coal.

15. Gas Clean-Up

Gas treatment is classified as an unsolved problem because it has not been attempted or demonstrated in the field. Gas analyses, however, indicate that only existing technology is required for gas clean-up which is primarily a developmental problem.

Coal gas from coke ovens or Lurgi gasifiers contains heavy tars and much particulate matter. Extensive and relatively expensive clean-up is required for these gases, and the highly viscous coal tars tend to plug valves or other equipment.

In contrast gas from UCG is much cleaner. The condensed liquids cause fewer problems than typical coal tars because of the difference in their physical properties. The liquids from UCG have a low viscosity similar to that of oils. None of the material has a boiling point above 780 K (950° F). Almost a quarter of the more typical coal tar derived from the laboratory carbonization of Hanna No. 1 coal was composed of residue with a boiling point above 810 K (1000° F) (17).

Particulate concentrations and compositions have been reported as well as trace metal analyses (18). During forward combustion particulate loading has varied from 0.05 to 0.90 gm/m^3. About 1/2 to 2/3 weight fraction of the particulate matter collected falls in the submicron range. Analyses indicate that it consists of partially carbonized coal and coal char.

Sulfur is produced in the form of hydrogen sulfide and no sulfur dioxide has been measured. Hydrogen sulfide, of course, can be scrubbed much more easily from the gas than sulfur dioxide.

Gas production temperatures usually range between 510-590 K (450-600° F). Thus, high temperature clean-up is not needed, and existing technology appears to be adequate for gas treatment.

SUMMARY AND CONCLUSIONS

Fifteen major technical problems associated with UCG have been discussed. Ten problems have been largely solved, five remain unsolved. Of the five, it is believed that only two, subsidence and excessive water influx, can present potentially major obstacles to commercialization of UCG. The Laramie Energy Research Center has had virtually no field experience with either problem because they become major ones only with large well patterns which have yet to be field tested. However, proposed large area field experiments should determine within the next few years if these two problems can be resolved favorably.

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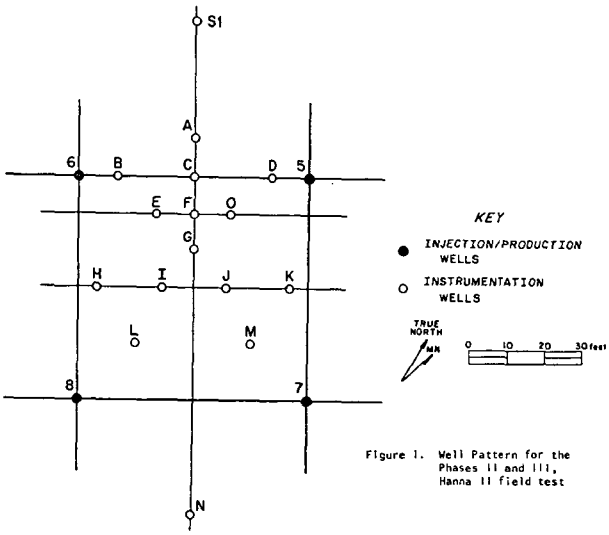

Figure 1. Well Pattern for the Phases II and III, Hanna II field test