THE UNDERGROUND GASIFICATION OF A SUBBITUMINOUS COAL

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INTRODUCTION

The recently recognized energy shortage has generated an upsurge in government research devoted to both improving current technology to better utilize known energy reserves and providing new technology which will allow the country to convert energy resources to reserves. Underground coal gasification (UCG) technology may play an important role in both of the above categories.

Sufficient technology is at hand to successfully produce a low-Btu gas from relatively shallow (<1000 ft.) deposits of bituminous, subbituminous and lignitic coal (1, 2, 3). Most recently the Bureau of Mines' Laramie Energy Research Center has conducted an underground gasification experiment at Hanna, Wyoming, in a 30 ft. thick seam of subbituminous coal at a depth of 400 ft. The results from Hanna have been more favorable than previous results in the U. S. and other countries (4) in two important categories: a gas of higher Btu content (125 Btu/scf) has been produced and during a 6½-month period of optimum operation there was little or no gas leakage from the underground system (3). However, applicability to deeper deposits (>1000 ft.) is not yet proven.

In order to evaluate UCG's feasibility, methods of measuring the physical and chemical occurrences in an inaccessible reaction zone must be developed. While experiments are underway to implant sophisticated instrumentation in the gasification pathway in the second UCG experiment at Hanna, such instrumentation would probably not be economically feasible in a commercial process. Consequently, it is of paramount importance to develop both inexpensive remote sensing and material and energy balance techniques to continuously evaluate the in situ process in order to maximize gasification efficiency and resource utilization. A material balance method derived by Elder et. al. (1) has been applied to data obtained from the first UCG experiment at Hanna. Results of these material balance calculations are presented as well as the problems involved in measuring factors necessary for performing a material balance.

GEOLOGICAL CONDITIONS

In attempting to build an underground reactor in a coal seam, important factors to be considered are the rate and pressure of water influx and the directional permeability of the coal. In addition, strata above and below the coal seam must have significantly lower permeabilities than the coal in order to prevent leakage from the reaction zone. The rate of water influx is related to both the permeability of the seam and to the hydrostatic pressure. In the experiment at Hanna, the seam of choice, the Hanna #1, is 180 to 200 feet below the water table. A 80-90 psig hydrostatic pressure is thereby imposed upon the reaction zone. Another important factor in the movement of water and gases within the seam is the directional nature and extent (both vertical and horizontal) of the natural

fractures within the coal seam (5, 6). A thorough understanding of these natural fractures should aid in development of true in situ process control.

The Hanna #1 seam used during this experiment is a 30-foot thick subbituminous coal seam lying at a depth of 350 to 400 feet. It dips to the northeast at 6 to 9°, is isolated by outcrop on three sides, and displaced by faulting on the fourth (2). Strata above and below the coal consist of less permeable shales with 15 feet above and 4 feet below the coal.

GASIFICATION TECHNIQUE USED AT HANNA

While many techniques have been used in UCG (7), the chosen method in the Hanna experiment was the percolation or filtration method. Success of this method depends on the development of sufficient permeability between vertical boreholes to maintain a sufficient flow of gasification agent and product gas. The critical step in development of the underground reactor is establishing the initial linkage between vertical boreholes, i.e., increasing air acceptance by some means. Therefore, the water and the natural fracture direction in the coal play obvious roles in affecting the UCG experiment. The initial permeability of the coal seam to injected air is quite low (1-10 milliDarcys). However, injection of air at pressures in excess of hydrostatic pressure expels water from the natural fracture system thereby increasing permeability. The degree of permeability increase is not predictable unless the natural fracture directions and the transmissivity of the coal are known. An experiment is planned to evaluate these parameters (8).

The most reliable method of linking boreholes prior to gasification is that of reverse combustion(3). A fire is ignited in the borehole to be vented and air is fed to this combustion zone by injection into an adjacent borehole. Thus the combustion front propagates countercurrent to the gas flow. This is in contrast to forward combustion wherein the combustion front proceeds in the same direction as the gas flow. The practical advantages of a reverse combustion mode over a forward combustion mode are:

1. The possibility of tars, produced from carbonization, plugging the natural fractures in the coal is obviated because the tars are not driven into the coal ahead of the combustion zone.

2. Directional control of combustion front movement is attained because the combustion front will proceed toward the source of air.

During establishment of linkage between wellbores using reverse combustion, two distinct phases have been found by monitoring air injection rate and pressure. Initially air is injected at relatively high pressure (250-300 psig) and low flow rates for a period of several days. During this time a narrow combustion front proceeds toward the source of air. When breakthrough between wellbores occurs, an abrupt drop in pressure occurs after which the flow of gas is relatively unrestricted. The gas produced during the linkage process is usually of high Btu content (approx. 175-200 Btu/scf) with high methane and low carbon monoxide content characteristic of a carbonization gas. However, once breakthrough is achieved allowing high volume-low pressure gas flow, gasification rather than carbonization becomes the predominant mode. Gasification is characterized by high carbon monoxide and low methane content in the product gas.

Thus a gasification scheme using the percolation method consists of two regimes, one of linking at high pressure and the other of gasification at low pressure. The linking process, being of short duration and low gas flow rates,

utilizes only a small fraction of the coal that is eventually affected between a pair of boreholes. Due to the high pressure involved, leakage from the system can be severe (75% gas loss) during the linking phase. Leakage during gasification has not been observed at Hanna. The seam water apparently acts as an effective gas seal during this low pressure operation (3).

FACTORS INVOLVED IN A MATERIAL BALANCE

A prerequisite for calculating a material balance on a system is a detailed knowledge of the reactants and products. In the case of UCG, it is impossible to determine the precise stoichoimetry of the coal to be gasified. A chemical and mineralogical examination of a core taken from the Hanna #1 coal seam reveals the lack of homogeneity with respect to depth. Table 1 lists the ash content, fixed carbon/volatile matter ratio, and C/H ratio of samples from a 30-foot core.

TABLE 1. - Core Analysis of Hanna #1 Coal Seam as a Function of Depth

Depth	% Ash 1/	Fixed Carbon/ Volatile Matter	C/H Ratio 2/
378.7	27.4	1.00	12.5
379.3	21.6	1.05	12.9
381.5	39.4	0.70	11.7
383.0	4.6	1.29	13.8
383.5	8.8	1.04	12.6
384.0	19.2	1.00	12.5
384.5	11.8	1.13	12.9
385.5	19.7	1.04	12.8
386.0	24.5	0.94	12.0
386.5	14.0	1.07	13.2
387.0	9.0	1.06	12.4
387.5	9.4	1.19	13.2
388.0	6.2	1.08	12.9
388.5	9.7	1.04	13.3
389.0	21.7	1.02	12.9
390.0	20.5	1.03	12.1
391.5	36.7	0.21	14.3
392.0	14.5	0.77	13.4
393.0	3.8	1.06	12.8
393.5	9.7	1.00	13.0
394.0	14.4	1.06	12.9
394.5	29.3	0.86	11.9
395.0	24.1	1.03	12.8
396.0	15.1	1.04	12.9
396.5	14.9	1.10	13.1
397.0	15.7	1.09	13.4
399.0	16.8	1.26	13.6
400.0	6.4	1.33	13.8
400.5	7.1	1.19	13.4
401.0	4.3	1.17	13.5
402.0	11.5	1.13	13.1
402.5	23.2	1.06	12.9

1/ Moisture free basis
2/ Moisture and ash free basis

MATERIAL BALANCE CALCULATIONS

Material balance equations may be written as follows:

Hydrogen Balance (H): H (from char) + H (from volatile matter) + H (from formation water)

= H (total in products) 1)

Carbon Balance (C): C (from char) + C (from volatile matter) = C (total in products) 2)

Oxygen Balance (Ø): Ø (from char) + Ø (from volatile matter) + Ø (from formation water)

= Ø (total in products) - Ø (from air) 3)

Then let:

x = pounds of char entering the reaction zone
y = pounds of volatile matter entering the reaction zone
z = pounds of water entering the reaction zone

Substituting the data from Table 2 into the material balance equations:

$H = 0.0083x + 0.116y + 0.111z$
$C = 0.970x + 0.498y$
$Ø' = 0.0003x + 0.347y + 0.889z$
Where Ø' = Ø (total in products) - Ø (from air)

Solving these equations for x, y and z with quantities expressed in pounds:

$x = 1.10C + 0.93Ø' - 7.45H$
$y = -0.12C + -1.82Ø' + 14.55H$
$z = 0.05C + 1.84Ø' - 5.67H$

From Table 2 the weight ratio of volatile matter to char is 0.92; the weight ratio of moisture and ash free (maf) coal to char is 1.92; and the weight ratio of maf coal to volatile matter is 2.08.

Therefore:
1.92x = weight of maf coal completely gasified and
2.08 (Y - 0.92x) = weight maf coal carbonized only

This material balance has been applied to a 6½-month operational period in five day increments. During this period both nitrogen and argon balances showed that there was little or no leakage from the underground system and thus a leak free system is assumed in the material balance. Additional assumptions are steady state conditions during the period considered, carbonization at 900°C, no condensation of products prior to gas sampling at the surface, no reactions of oxygen with any materials other than coal, and the laboratory carbonization assays indicate the stoichiometry of the char and volatiles under seam reaction conditions. The results of this material balance are listed in Table 3 along with average air injection rates, average gas production rates and average product gas heating values for the periods indicated.

The total amount of coal affected during the period considered was 2986 tons with 1171 tons carbonized only and 1815 tons completely gasified. These results are based on the linkage and gasification of three pathways of 80, 90, and 100 feet, respectively, radiating from the original ignition point to three different wellbores used as air injection points. Assuming that a cylinder of coal 30 ft. in diameter was accessible to gasification for each pathway, approximately 4700 tons of maf coal were available for gasification. Therefore, the coal utilization efficiency was 63%. From Table 3 the average energy recovered from the coal affected was 58%. The product of these two efficiencies yields an overall energy

These data indicate that while the ash content varies widely with respect to depth in the seam of interest, the ratio of fixed carbon to that of volatile matter and the C/H ratio remain relatively constant.

In assessing a material balance for a UCG experiment, several assumptions must obviously be made. It is difficult to measure the total quantities of water which are gained or lost by the system. More importantly it is difficult to directly measure the amount of coal affected and the manner in which it was affected. However, excavation of previous UCG experiments and laboratory simulations have shown that the process occurs in two discrete steps: carbonization only and complete gasification. In UCG a stream of the gasification agent is passed over the surface of the coal with carbonization occurring first followed by complete gasification of the remaining char. Water from the coal itself or natural groundwater influx from the seam is present at or near the region of reaction. For practical purposes air, volatile matter from coal, char from coal, and water are present in the reaction zone where the carbonization-gasification processes occur.

Although it is not difficult to set up a material balance in theory, practical considerations of UCG make it extremely difficult to measure all of the quantities involved. Obtaining a material balance thus involves:

1. Measurement of the gasification agent (air).

2. Assuming that the material to be gasified enters the system in two discrete parts: (a) the products of carbonization of the coal at 900°C, and (b) the char remaining after carbonization.

3. Estimating the quantity of water entering the underground system.

4. Measuring the volume and composition of the products.

The application of Elder's method (1) of material balance to the Hanna #1 coal is based on a precision carbonization assay at 900°C, the results of which are listed in Table 2 along with the ultimate analysis.

TABLE 2. - Elemental distribution in coal, char and volatile matter from 100 pounds of moisture and ash free Hanna #1 Coal

Element	Coal		Char		Volatile Matter	
	wt. %	Pounds	wt. %	Pounds	wt. %	Pounds
H	6.04	6.04	0.83	0.43	11.60	5.61
C	74.33	74.33	97.02	50.34	49.82	23.93
O	16.67	16.67	0.03	0.02	34.65	16.65
N	1.94	1.94	0.93	0.48	3.04	1.46
S	1.02	1.02	1.19	0.63	0.81	0.39
Totals	100.00	100.00	100.00	51.90	99.92	48.04

TABLE 3. - Five Day Averages of Operating Data and Material Balance Results

Starting Date of 5 Day Period	Air Injection Rate (MM scf/day)	Dry Gas Production Rate (MM scf/day)	Heating Value (Btu/scf)	Tons of MAF Coal Carbonized Only (tons/day)	Tons of MAF Coal Completely Gasified (tons/day)	Total MAF Coal Affected (tons/day)	Energy Recovery Efficiency (%)
9/16/73	1.20	1.40	61	16.0	0.9	16.9	20
9/21/73	0.69	0.97	134	13.5	1.6	15.1	33
9/26/73	0.82	1.26	150	15.7	2.9	18.6	39
10/01/73	0.99	1.48	138	2.6	9.3	11.9	67
10/06/73	1.06	1.78	163	8.7	9.9	18.6	61
10/11/73	1.11	1.89	162	13.0	8.9	21.9	54
10/16/73	1.08	1.76	153	11.0	8.4	19.4	54
10/21/73	1.03	1.56	136	9.6	6.9	16.5	50
10/26/73	1.06	1.60	134	7.5	7.9	15.4	54
11/01/73	0.83	1.44	158	9.3	6.7	16.0	55
11/06/73*	0.71	1.04	112	-4.2*	8.1	--*	--*
11/11/73	1.08	1.63	132	4.2	9.3	13.5	61
11/16/73	1.23	1.79	129	6.9	9.4	16.3	55
11/21/73	1.20	1.76	129	5.9	9.5	15.4	56
11/26/73	1.36	1.91	114	4.2	10.5	14.7	57
12/01/73	1.15	1.69	125	6.8	8.4	15.2	53
12/06/73	1.09	1.57	109	3.6	8.1	11.7	56
12/11/73	1.25	1.91	136	-1.6*	13.7	--*	--*
12/16/73	1.22	1.81	126	7.2	9.0	16.2	55
12/21/73	1.29	1.86	110	0.2	11.2	11.4	69
12/26/73	1.22	1.72	103	-4.7*	12.0	--*	--*
1/01/74	0.79	1.01	75	-4.6*	7.3	--*	--*
1/06/74	0.96	1.21	68	-5.9*	8.6	--*	--*
1/11/74	0.96	1.13	52	-5.1*	7.5	--*	--*
1/16/74	0.94	1.14	70	1.4	5.5	6.9	44
1/21/74	0.58	0.77	96	3.3	3.3	6.6	44
1/26/74	0.78	1.13	125	5.7	5.3	11.0	50
2/01/74	1.09	1.84	168	7.7	11.2	18.9	63
2/06/74	1.20	1.98	176	16.9	9.2	26.1	51
2/11/74	1.39	2.14	153	7.0	13.1	20.1	62
2/16/74	1.43	2.35	187	14.4	14.4	28.8	59
2/20/74	0.69	1.66	200	28.7	13.5	42.2	42
2/24/74	2.06	2.85	118	-4.4*	20.4	--*	--*
3/01/74	1.56	2.21	117	-9.8*	18.1	--*	--*
3/06/74	1.89	2.75	128	3.2	17.2	20.4	67
3/11/74	0.66	1.48	182	-8.5*	14.3	--*	--*
3/16/74	1.51	2.25	131	-2.3*	16.0	--*	--*
3/21/74	0.10	0.34	229	-6.9*	5.5	--*	--*
3/26/74	0.00	0.05	275	--*	--*	--*	--*

* These data are not significant because abrupt variations in flow rates preclude a steady state system.

recovery efficiency of 37% based on results of this material balance calculation.

This material balance is only a chemical interpretation of the process based on many assumptions. The areal and vertical sweep efficiencies are unknown. In addition, this first experiment was designed not to optimize operating parameters but to provide preliminary information for designing other experiments to evaluate UCG feasibility. Even so, the results are encouraging. The overall energy efficiency for the period considered is higher than that achieved in any previous UCG experiment for the length of time considered here. Physical assessment will include coring and downhole measurements to better establish the sweep efficiencies and the geometry of the coal area affected. These data will give a much better idea of the overall resource utilization efficiency than the material balance calculations.

FUTURE RESEARCH

A second experiment (8) at Hanna is presently underway utilizing an oxygen blown system, an improved well linkage system, and in situ instrumentation consisting of both active and passive acoustic techniques, surface and subsurface resistivity, and in situ temperature and pressure measurements to better define the combustion zone. A "line drive" system will be initiated. This involves movement of a 60-foot long combustion front at right angles to the major natural permeability direction in the coal providing intimate contact between the gasification agent and the coal. Coal utilization efficiency should be improved over that estimated from the first UCG experiment. A target of 50% overall energy efficiency rather than the 37% estimated here for the first experiment has been set. This second experiment should lead to development of process control and process evaluation techniques as well as significantly improved process interpretation for determining the feasibility of UCG.

CONCLUSIONS

A UCG experiment has been successfully conducted in a thick seam of subbituminous western coal with encouraging results. Problems of gas leakage and the ability to link wellbores successfully have not occurred during the Hanna project so long as reverse combustion was used to link adjacent wellbores. Seam water, rather than posing a problem, appeared to be an asset in preventing gas leakage in the underground reaction system. A material balance technique based on the carbonization properties of coal has been used to estimate an energy recovery efficiency of 58% from the coal affected, a coal utilization efficiency of 63%, and an overall energy recovery efficiency of 37%. Many problems remain to be solved in UCG such as a greater degree of process control, but results of the first UCG experiment are especially encouraging even though it was not designed to optimize operating parameters. The second UCG experiment now underway should yield higher coal utilization efficiencies and offer a feasible technique for recovering energy from coal seams unsuited to current coal mining techniques.

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