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LLNL Underground-Coal- Gasification Project Quarterly Progress Report— July through September 1981

Scientific Editor: D. R. Stephens
General Editor: Wallace Clements

November 9, 1981

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LLNL Underground Coal Gasification Project Quarterly Progress Report— July through September 1981

SUMMARY

We have continued our laboratory studies of forward gasification in small blocks of coal mounted in 55-gal drums. A steam/oxygen mixture is fed into a small hole drilled longitudinally through the center of the block, the coal is ignited near the inlet and burns toward the outlet, and the product gases come off at the outlet. Various diagnostic measurements are made during the course of the burn, and afterward the coal block is split open so that the cavity can be examined. This visual inspection of the gasification cavities in laboratory-scale experiments—an observation that is usually impossible in large field experiments—is an important aid to our understanding of the *in situ* gasification process. For the three coals studied so far (two from Wyoming and one from Washington), we have found considerable variation in cavity shape from one coal to another, although the product-gas heating values have been very similar. In our most recent tests, reported here, we have found that injecting a mixture of steam/oxygen in about a 1/1 ratio appears to be optimum; by contrast, injection of pure oxygen gives a relatively narrow burn cavity and a product gas of low heating value. Variation of the steam/oxygen flow rate seems to have little effect.

Development work continues on our mathematical model for the small coal block experiments. The objective is to improve our understanding of the physical and chemical processes governing the burning of the coal and the growth of the cavity within the block. We intend to adapt the model, later, to larger-scale coal block experiments and finally to full-scale field experiments, hoping to obtain scaling laws and other insights as a result. Here we report our recent studies with the model, in which we have investigated what happens to the water in the coal. We find that for coal surface temperatures above about 1300 K, the only gases emerging from the coal are H_2 , CO, and hydrocarbons, whereas for surface temperatures below about 1000 K, only steam and possibly hydrocarbons emerge. These two temperature zones may represent zones of stability or steady state.

Preparations for the large block experiments at a coal outcrop in the Tono Basin of Washington State have required steadily increasing effort with the approach of the scheduled starting time for the experiments (fall 1981). The operational plan for these experiments has been completed and is included here.

Also in preparation is the deep gasification experiment, Tono 1, planned for another site in the Tono Basin after the large block experiments have been completed. The specific site for this gasification test has been selected on the basis of preliminary characterization studies of the general area. Some results of the preliminary characterization studies are given here, along with the plan for further drilling of wells at the selected site to localize the site characterization and prepare for the experiment.

Wrap-up work continues on our previous gasification experiments in Wyoming. Results of the postburn core-drilling program at Hoe Creek 3 are presented here.

Since 1976 the Soviets have been granted four U. S. patents on various aspects of the underground coal gasification process. These patents are described here, and techniques of special interest are noted.

Finally, we include ten abstracts of pertinent LLNL reports and papers completed during the quarter. Nine of these represent the nine LLNL papers presented at the Seventh Underground Coal Conversion Symposium, hosted by LLNL and held at the Stanford Sierra Lodge, Fallen Leaf Lake, Calif., Sept. 8-11, 1981.

INTRODUCTION

A major objective of the U. S. Energy Program is to develop environmentally acceptable and economically sound ways to produce energy from the nation's vast coal reserves. The Department of Energy (DOE) has sponsored a number of field projects to determine the feasibility of converting coal into a clean, efficient energy source by underground coal gasification (UCG). The basic goal of the Lawrence Livermore National Laboratory (LLNL) project, as a part of DOE's UCG program, is to develop a process for producing medium-heating-value gas that can be economically upgraded to pipeline quality gas or used to produce transportation fuels such as methanol or gasoline.

Following the Hoe Creek series of UCG tests in Wyoming, for which the gasification phase ended in 1979 and subsequent experimental projects have been largely completed, LLNL's next major field program is in the State of Washington. An *in situ* coal gasification project is being initiated at a site in the Tono Basin owned by the Washington Water Power Company. This project is jointly supported by the Department of Energy and the Gas Research Institute. It will begin with several large-scale, laboratory-type gasification experiments—called "large block experiments"—to be done at a site where the Big Dirty coal seam outcrops in a mine. These initial experiments will provide information needed for final planning of

two larger field experiments to be done from the surface at locations where the Big Dirty coal seam is 500 feet or more underground. One of these field experiments (Tono 1, discussed in this report) will link the vertically drilled injection and production wells by a horizontal hole in the coal seam, directionally drilled from the surface, while the other (Tono 2) will link the wells by reverse combustion.

The overall program in the Tono Basin is managed by the Laramie Energy Technology Center (LETC). Participating in the various technical aspects are LETC, LLNL, Sandia National Laboratories, the Morgantown Energy Technology Center, the Washington Irrigation and Development Company (WIDCO), Pacific Power and Light, and the State of Washington. LLNL is responsible for the gasification phase.

This report covers UCG Project work done by LLNL in the third quarter of 1981. Besides the current field work in the Tono Basin, mentioned above, LLNL is also carrying on analyses of data from the Hoe Creek field experiments, laboratory gasification experiments done with small blocks of coal from seams of interest, development of a computer model to aid our understanding of the UCG process, and review of earlier UCG work done here and abroad. All of these subjects are discussed in this report.

LABORATORY-SCALE COAL GASIFICATION EXPERIMENTS

The use of small tests to simulate large-scale phenomena is always subject to problems that arise from the difficulty of scaling all the important physical and chemical processes. In practice it is generally not possible to scale all processes correctly, and so the small-scale tests may not be true

simulations of the large-scale behavior. Coal gasification is a result of a large number of complicated interactions (e.g., fluid flow, heat transfer, mass transfer, chemical reactions, mechanical and thermal alterations), and accordingly the scaling problems are severe. For example, the mechanical

spalling of material is certainly a length-scale-dependent phenomenon, hence one which is probably not well represented in small-scale experiments. Also, the relative importance of radiant and conductive heat transfer as well as forced and free convection are undoubtedly poorly represented in small-scale tests.

In spite of these shortcomings, small-scale laboratory tests are still attractive because they allow the observation of gasification cavities and are relatively economical. For these reasons we have in the past conducted a number of simple laboratory tests in which sample blocks of coal were gasified to determine initial cavity shape as a function of coal type.^{1,2} Recently we have conducted more complete tests in which most of the important process variables have been monitored.

In the laboratory block tests, sample blocks of coal contained in small reactors are gasified using steam/oxygen injection and a drilled link between the injection and production points. The overall objectives of the continuing series of laboratory block tests are divided between short-term goals aimed at our next field experiment and longer-range goals aimed at a better understanding of *in situ* coal gasification. Our short-term goals include:

- Developing an improved gas-analysis stream cleanup system for use during laboratory and field tests, with special emphasis on continuous measurement of water content.
- Debugging the software used in data acquisition and reduction.
- Completing a shakedown of our new mobile facility (trailer-mounted) which combines the three functions of gas analysis, data acquisition, and control center.

Our long-term goals include:

- Obtaining data on performance and cavity development as functions of coal type, gas flow rate, and injected gas composition.
- Obtaining data on the relative importance of heat and mass transfer by using amorphous carbon as the solid to be gasified.
- Obtaining cavity growth information by use of radiography.
- Obtaining results needed for the verification of gasification models.

EXPERIMENTAL APPARATUS AND PROCEDURES

The basic coal reactors we use consist of modified 55-gal drums. Coal blocks roughly the size of the drums are collected at the various mines and shipped in water to the laboratory where they are potted into the drums with plaster of Paris. The coal block is placed in the drum so that the bedding planes of the coal are parallel to the axis of the drum. A 5/16-in. hole is drilled longitudinally through the center of the block to provide the gas flow path. A new reactor is constructed for each run.

The instrumentation used during each run includes thermocouples, orifice meters, pressure gauges, and gas analysis equipment. Three of the thermocouples are "traveling thermocouples"; they are placed in three holes drilled perpendicular to the center borehole, and they are movable to any depth desired in the holes.

A run generally lasts 3 to 5 hours. It begins with the introduction of an ignition gas mixture composed of air, oxygen, and argon. When these flows are established the igniter is switched on. After about 15 minutes the burn is usually well established and a transition is made to a planned feed-gas mixture and flow rate. In the runs to date this has meant the replacement of the air flow with steam flow. At intervals the traveling thermocouples are traversed across the burn and a scheduled series of flow rate and/or compositional changes is performed. During the latter stages of the burn it is often necessary to cool the product gas by injecting water into the product line.

Further details on construction and operation of the system are provided elsewhere.³

PREVIOUS RESULTS

The first series of runs (see Ref. 3 for details) with the 55-gal-drum reactors was aimed at determining the influence of coal type on performance. A steam/oxygen ratio of 2/1 was used. Each run lasted 5 hours, during which time the flow rate was increased in proportion to the square of the elapsed time (t^2 flow schedule). The initial oxygen flow was 3 mmol/s, and the maximum flow at the end of the test was 25 mmol/s of oxygen.

Three coals were used in this initial series of tests: Hanna coal from the Arch Mineral Seminole No. 2 mine near Hanna, Wyoming; Wyodak coal from the Kerr-McGee Jacobs Ranch near Gillette, Wyoming; and WIDCO coal from the Big Dirty seam of the WIDCO mine near Centralia, Washington. The gasification results are summarized in Table 1 and the coal compositions are given in Table 2.

We found that the gasification results as measured by product gas composition were only a weak function of coal type; the results in Table 1 are reasonably similar for the three coals. On the other hand, we found that the appearance of the cavity cross section perpendicular to the flow direction was a strong function of coal type. The WIDCO coal yielded a roughly circular rubble-filled cavity, the Hanna coal resulted in a circular open cavity of considerably smaller size with a large char ring, and the Wyodak coal exhibited an asymmetric open cavity elongated in the direction perpendicular to the bedding planes.

RECENT RESULTS

Our most recent series of tests have addressed the influences of flow schedule and injected gas composition. We have compared the results of t^2 and $t^{1/2}$ flow schedules (i.e., flow proportional to t^2 and to $t^{1/2}$). In addition we have run tests using steam/oxygen ratios ranging from 0/1 to 3/1. Most

of this work has been done with Wyodak coal due to its availability and uniformity. However, one run used the WIDCO coal, which is of particular interest to us because of the large block experiments to be done this fall at the WIDCO mine near Centralia, Washington.

An additional diagnostic aid has been used on most of the recent tests. Radiograms (x-ray pictures) of the coal blocks are taken periodically to record the development of the cavity as gasification progresses.

Effect of Varying the Flow Schedule

The importance of a particular flow schedule was examined in runs WYD-2 and WYD-3 with Wyodak coal. A 2/1 steam/oxygen feed was used, with the oxygen flow schedule for each experiment as shown in Fig. 1. The WYD-2 run used a t^2 oxygen flow schedule and the WYD-3 a $t^{1/2}$ schedule. In both cases a 25-mmol/s maximum flow of oxygen was reached. The time durations of the experiments were chosen so that the total amount of oxygen injected would be the same for each.

The gasification results of the two tests are given in Table 3, and the coal compositions in Table 4. Table 3 indicates very little difference in the two results. The small difference in gas heating value is probably within the normal variation from experiment to experiment. No marked difference in cavity shape was observed.

TABLE 1. Comparison of gasification results for three coals.

Coal type	WIDCO	Hanna	Wyodak
Sample number	WID-3	HAN-2	WYD-2
Dry-product-gas composition (mole fractions):			
H ₂	0.37	0.36	0.37
CH ₄	0.024	0.021	0.020
CO	0.26	0.32	0.27
CO ₂	0.32	0.27	0.32
C ₂ H ₄	0.005	0.005	0.004
H ₂ S	0.0024	0.0059	0.0012
Product-gas heat of combustion (kJ/mol)	208	219	204
Product-gas heat of combustion per mole of injected oxygen (kJ/mol)	661	687	631
Fraction of coal energy in combustible product gas ^a	0.74	0.73	0.67

^aFraction based on consumed coal energy estimated from produced carbon.

TABLE 2. Compositions of the three coals.

Coal type	WIDCO	Hanna	Wyodak
Sample number	WID-3	HAN-2	WYD-2
Weight fraction water	0.20	0.12	0.26
Weight fraction ash	0.14	0.12	0.03
Coal chemistry (dry basis):			
H/C	0.92	0.90	1.01
O/C	0.19	na ^a	na ^a
S/C	0.0034	0.0042	0.0022

^aNot applicable.

TABLE 3. Comparison of two flow-rate schedules in gasifying Wyodak coal.

Sample number	WYD-2	WYD-3
Flow rate schedule (time dependence)	t^2	$t^{1/2}$
Dry-product-gas composition (mole fractions):		
H ₂	0.37	0.37
CH ₄	0.020	0.019
CO	0.27	0.24
CO ₂	0.32	0.35
C ₂ H ₄	0.004	0.003
H ₂ S	0.0012	0.0005
Product-gas heat of combustion (kJ/mol)	204	196
Product-gas heat of combustion per mole of injected oxygen (kJ/mol)	631	592
Fraction of coal energy in combustible product gas ^a	0.67	0.63

^aFraction based on consumed coal energy estimated from produced carbon.

TABLE 4. Compositions of the two Wyodak coal samples in the flow rate tests.

Sample number	WYD-2	WYD-3
Weight fraction water	0.26	0.24
Weight fraction ash	0.032	0.045
Coal chemistry (dry basis):		
H/C	1.01	0.86
O/C	na ^a	0.21
S/C	0.0022	0.0022

^aNot applicable.

FIG. 1. Flow schedules for the WYD-2 and WYD-3 experiments.

Effect of Varying the Steam/Oxygen Ratio

A series of three runs with Wyodak coal was performed in which the steam/oxygen ratio was varied from 0/1 to 3/1. In each of these tests a $t^{1/2}$ flow schedule was used, reaching a maximum oxygen flow of 25 mmol/s. The tests each lasted 3-1/2 hours.

Table 5 gives the results of these tests, and Table 6 gives the coal compositions. The results indicate a considerable variation with steam/oxygen ratio. The pure oxygen run yielded very much poorer results than the 2/1 and 3/1 steam/oxygen runs. Best performance was with the 2/1 ratio. The falloff in performance between the 2/1 and 3/1 ratios is not as dramatic as that between the 2/1 and 0/1 ratios, but is probably real, although more ex-

periments would be needed to determine the exact magnitude of the difference.

Included in Table 5 is the range of temperatures recorded by a thermocouple placed approximately 12 in. downstream of the end of the injection tube. In the case of the 0/1 test this thermal well was immediately consumed and no readings are available, but note the similarity in temperatures for the 2/1 and 3/1 runs. This similarity may be a result of kinetic limitation of endothermic reactions at this temperature level in the system, but more probably is a result of the considerable gas evolution from the coal which greatly dilutes the influence of relatively small changes in injected composition.

Postburn examination and radiographic data do not indicate significant differences in the shapes of the burn cavities for the 2/1 and 3/1 tests.

TABLE 5. Gasification results for three steam/oxygen ratios in Wyodak coal.

Sample number	WYD-4	WYD-3	WYD-5
Steam/oxygen (mole ratio)	0/1	2/1	3/1
Dry-product-gas composition (mole fractions):			
H ₂	0.16	0.37	0.37
CH ₄	0.004	0.019	0.022
CO	0.28	0.24	0.18
CO ₂	0.51	0.35	0.47
C ₂ H ₄	0.002	0.003	0.004
H ₂ S	0.0005	0.0005	0.0010
Product-gas heat of combustion (kJ/mol)	130	196	176
Product-gas heat of combustion per mole of injected oxygen (kJ/mol)	203	592	371
Fraction of coal energy in combustible product gas ^a	0.34	0.63	0.56
Temperature at 12-in. thermocouple position (°C)	—	1210-1270	1220-1280

^aFraction based on consumed coal energy estimated from produced carbon.

TABLE 6. Compositions of the Wyodak coal samples in the steam/oxygen ratio tests.

Sample number	WYD-4	WYD-3	WYD-5
Weight fraction water	0.27	0.24	0.26
Weight fraction ash	0.045	0.045	0.056
Coal chemistry (dry basis):			
H/C	0.98	0.86	1.03
O/C	0.16	0.21	0.15
S/C	0.0031	0.0022	0.0035

TABLE 7. Gasification results with two steam/oxygen ratios in WIDCO coal.

Sample number	WID-4	WID-3
Steam/oxygen (mole ratio)	1/1	2/1
Dry-product-gas composition (mole fractions):		
H ₂	0.36	0.37
CH ₄	0.022	0.024
CO	0.35	0.26
CO ₂	0.25	0.32
C ₂ H ₄	0.003	0.005
H ₂ S	0.0019	0.0024
Product-gas heat of combustion (kJ/mol)	226	208
Product-gas heat of combustion per mole of injected oxygen (kJ/mol)	653	661
Fraction of coal energy in combustible product gas ^a	0.74	0.74
Temperature at 12-in. thermocouple position (°C)	1200–1290	1220–1300+

^aFraction based on consumed coal energy estimated from produced carbon.

TABLE 8. Compositions of the WIDCO coals in the steam/oxygen ratio tests.

Sample number	WID-4	WID-3
Weight fraction water	0.22	0.20
Weight fraction ash	0.093	0.14
Coal chemistry (dry basis):		
H/C	1.15	0.92
O/C	na ^a	0.19
S/C	na ^a	0.0034

^aNot available at this time.

However, the 0/1 test yielded a cavity that grew much more uniformly as a cylinder from injection to production end of the system than the cavities in the other runs. Also, the width of the final cylindrical cavity in the 0/1 test was considerably less than the width of the widest portion of the cavities for the other tests.

Two runs were performed in WIDCO coal in which two steam/oxygen ratios, 2/1 and 1/1, were used. These runs used a t^2 flow schedule with a maximum oxygen flow of 25 mmol/s. Table 7 gives the gasification results and Table 8 the coal chemistry for these runs. Overall performance for these two runs was similar, with the 1/1 run yielding a slightly higher heating value but equal product-gas heat of combustion per mole of in-

jected oxygen and equal combustible-gas energy fraction. There is a considerable difference in CO and CO₂, reflecting the change in available steam. The H₂ level, however, is little influenced by this steam difference. The measurements at the 12-in. thermocouple indicate similar temperatures.

The duration of the WID-4 test (1/1 steam/oxygen) was extended 1/2 hour beyond the normal period so that the steam/oxygen ratio could be changed. We wanted to compare the performance of 1/1 and 2/1 steam/oxygen mixtures in the same block of coal and thus avoid the sample-to-sample variability that is a problem with WIDCO coal. Table 9 compares the results for the last half-hour of the 1/1 steam/oxygen burn (at 25 mmol/s of oxygen) with the results for the final half-hour of the 2/1 burn (at 25 mmol/s of oxygen). The results are similar to those for the comparison of the WID-3 and WID-4 tests, with the exception of the results for kJ/mole O₂ and combustible energy fractions. Those for the short-duration tests in the same blocks indicate a poorer performance for the 2/1 ratio, while those for the longer-term WID-3 and WID-4 comparison indicate equal performance. However, since the 2/1 test was done at the end of the WID-4 run, more coal had been burned away than during the 1/1 period. This difference may partly explain the difference in results. More experimentation is

TABLE 9. Comparison of results for two steam/oxygen ratios in the same sample block of WIDCO coal (WID-4).

Steam/oxygen (mole ratio)	1/1	2/1
Dry-product-gas composition (mole fractions):		
H ₂	0.34	0.34
CH ₄	0.018	0.019
CO	0.37	0.30
CO ₂	0.25	0.31
C ₂ H ₄	0.0038	0.0040
H ₂ S	0.0016	0.0004
Product-gas heat of combustion (kJ/mol)	222	205
Product-gas heat of combustion per mole of injected oxygen (kJ/mol)	562	469
Fraction of coal energy in combustible product gas ^a	0.71	0.65
Temperature at 12-in. thermocouple position (°C)	1200-1280	1220-1280

^aFraction based on consumed coal energy estimated from produced carbon.

FIG. 2. Product-gas heat of combustion as a function of steam/oxygen ratio.

FIG. 3. Product-gas heat of combustion per mole of injected oxygen as a function of steam/oxygen ratio.

necessary to determine which, if either, of these results is representative.

The overall performance of the block gasifications as a function of steam/oxygen ratio is summarized in Figs. 2 and 3. In Fig. 2 the product-gas

heat of combustion is seen to increase as the steam/oxygen ratio is decreased, up to about a 1/1 ratio, at which point it drops rapidly. Both the Wyodak and WIDCO coals exhibit the same trends.

In Fig. 3 the dry-product-gas heat of combustion per mole of injected oxygen is shown to behave in a manner similar to the heat of combustion results. However, on this basis the WIDCO coal yields conflicting results. If the long-term results are used for the WIDCO coal, the dotted curve would indicate that the optimum steam/oxygen ratio may lie between 1/1 and 2/1, while if the short-term single block results are used then the optimum would appear to lie at or below the 1/1 ratio (similar to that of the heat of combustion curve in Fig. 2). Figure 3 implies that the WIDCO and Wyodak coals can be considered on a single curve, a result which needs further experimentation to verify, as does the inconsistency in the WIDCO results.

CONCLUSIONS

From the work to date in laboratory-scale gasification of coal blocks, the following preliminary conclusions can be drawn:

- The WIDCO, Hanna, and Wyodak coals yield burn cavities whose cross sections differ in appearance.
- The difference in cavity appearance does not lead to large differences in product-gas heating value.

- The flow rate schedule does not seem to be an important variable.

- There appears to be an optimum in performance at a steam/oxygen ratio of about 1/1 for both the WIDCO and Wyodak coals.

- Pure oxygen yields a relatively narrow burn channel and a product gas of low heating value.

FUTURE PLANS

Our future work will concentrate on the following:

- More detailed analysis of the radiograms taken during past experiments.
- An attempt to obtain gas samples from the burn cavity.
- An attempt to obtain detailed thermal profiles in the vicinity of the cavity boundary.
- The use of a radiation-shielded thermocouple to confirm cavity gas temperatures.
- The use of amorphous carbon as a simple model system.
- The use of longer blocks.

—C. B. Thorsness

MATHEMATICAL MODELING: WHAT HAPPENS TO THE WATER IN THE COAL?

Underground coal generally contains water, sometimes only a few percent by weight, but other times one-third or more. We will consider the case where gasification occurs in a borehole or other cavity and heat from the combustion reactions flows into the solid coal, vaporizing the water. The resulting pressure drives the vapor through the dried coal toward the cavity. If the temperature near the surface of the coal is high enough, the vapor can react with the char to form H_2 and CO . There may be additional underground water that flows toward the cavity as the coal is being dried. Its fate is the same as that of the water originally in the coal. Some simple physical and chemical ideas will be used to explore the fate of the water.

We will consider several progressively more complicated situations. In all cases heat is flowing into the coal through the walls of the cavity, and the temperature decreases in a roughly exponential fashion with increasing distance into the coal. If the surface temperature (of the cavity wall) is above the boiling point there will be a drying front in the coal at about the depth where the temperature equals the boiling point. Both calculation and experiment show that this drying front is normally a centimeter or more beneath the surface of the coal. If carbon is being consumed the surface can regress at velocities as high as 0.001 cm/s, and the drying front moves ahead of it at the same velocity. If the surface moves slower so does the drying front, but even if

the surface is stationary the drying front will continue to move at some low velocity.

When water is vaporized at atmospheric pressure it expands roughly 1000-fold in volume, so if the drying front is moving at 0.001 cm/s the vapor released in 1 s will occupy a fraction of a cubic centimeter per square centimeter of the drying front. In coals that shrink on heating, there is a void volume left in the dry coal comparable to the amount of water removed, leaving an easy path for the vapor to expand into the borehole. Thus, the vapor can be expected to move on the order of 1 cm/s or less. Since the dried coal layer is at least 1 cm thick, the vapor will have on the order of 1 s to react with the dried coal. So there is more than enough time for steam to react with char, provided the temperature is high enough.

In addition to containing water, coal generally contains hydrocarbons, which evaporate or are released by pyrolysis at temperatures above about 800 K. Presumably these hydrocarbons cannot react with coal or water (except for some possible cracking of the hydrocarbons into lighter fractions). Thus we will ignore these volatile hydrocarbons, except for acknowledging that their combustion in the gas phase may provide part of the heat which drives the processes involving water.

GAS COMPOSITION AS A FUNCTION OF A REACTION PROGRESS VARIABLE, r

If the surface temperature exceeds 1200 to 1300 K, the endothermic steam/char reaction can occur:

Both products of this reaction are fuels and can burn in the cavity to provide the heat to drive the vaporization and the steam/char reaction. The remainder of this section is devoted mainly to showing that if the temperature is high enough for reaction (1) to occur, then conditions will be such that all of the water reacts and only H_2 and CO , plus volatile hydrocarbons, pass through the surface of the coal into the cavity.

If the temperature is high enough for the steam/char reaction to occur, it will also be high enough for the water-gas-shift reaction to reach equilibrium:

Equilibrium implies

$$K = \frac{[\text{CO}_2][\text{H}_2]}{[\text{CO}][\text{H}_2\text{O}]} \quad (3)$$

where K is the equilibrium constant and the square brackets indicate concentrations. It is convenient to express the concentrations in terms of a reaction progress variable, r . The value of r is the fraction of the initial water that has been consumed by reaction (1), but does not count the water shifted to H_2 by reaction (2). Note, however, that as water is consumed by reaction (1), the equilibrium shifts to the left in reaction (2), converting H_2 back to H_2O . Thus the maximum value of r is 1. (However, if there were an excess of water, reaction (1) would stop when all char was consumed with r less than 1.)

We can write equations for the conservation of atoms:

for hydrogen,

$$2[\text{H}_2] + 2[\text{H}_2\text{O}] = 2[\text{H}_2]_0 + 2[\text{H}_2\text{O}]_0 \quad (4)$$

for oxygen,

$$[\text{CO}] + [\text{CO}_2] + [\text{H}_2\text{O}] = [\text{CO}]_0 + 2[\text{CO}_2]_0 + [\text{H}_2\text{O}]_0 \quad (5)$$

for carbon,

$$[\text{CO}] + [\text{CO}_2] = [\text{CO}]_0 + [\text{CO}_2]_0 + r[\text{H}_2\text{O}]_0 \quad (6)$$

where the zero subscript indicates initial concentrations, which will usually be negligible except for $[\text{H}_2\text{O}]_0$. Equations (3)–(6) can be solved for the concentrations in terms of r and the initial concentrations. To make the concentrations dimensionless, let $C_x = [X]/[\text{H}_2\text{O}]_0$ and $Z_x = [X]_0/[\text{H}_2\text{O}]_0$, then

$$\begin{aligned} & (K-1)(C_{\text{H}_2\text{O}})^2 \\ & + [K(2r-1+Z_{\text{CO}})+2-r+Z_{\text{CO}_2}+Z_{\text{H}_2}]C_{\text{H}_2\text{O}} \\ & - (1+Z_{\text{H}_2})(1+Z_{\text{CO}_2}) = 0 \quad (7) \end{aligned}$$

$$C_{H_2} = 1 + Z_{H_2} - C_{H_2O} , \quad (8)$$

$$C_{CO} = 2r - 1 + Z_{CO} + C_{H_2O} , \quad (9)$$

$$C_{CO_2} = 1 - r + Z_{CO_2} - C_{H_2O} . \quad (10)$$

Equation (7) is quadratic in C_{H_2O} , so a general expression can be obtained, but it is quite complicated except for the special cases where r is either 0 or 1 and the Z 's are zero. When r is zero, the only valid solution is $C_{H_2O} = 1$ and all other concentrations are zero. When $r = 1$, the valid solution is $C_{H_2} = C_{CO} = 1$ with $C_{H_2O} = C_{CO_2} = 0$. (Note that if C_{H_2O} and C_{CO_2} vanish simultaneously, then Eq. (3) is satisfied for any values of C_{H_2} and C_{CO} .) The behavior of the concentrations for intermediate values of r is shown in Fig. 4 for $K = 0.5$, the approximate value for temperatures of interest (see Fig. 5). If K were zero, all of the curves would be straight lines and no CO_2 would be formed because all of the H_2O would react by reaction (1). As K increases, some of the H_2O reacts with CO for smaller values of r , increasing the amount of CO_2 formed as well as increasing the curvature of the species concentrations shown in Fig. 4. Regardless of the value of K , the solution for $r = 1$ is the same: one molecule of H_2 and one molecule of CO for each initial molecule of water.

FIG. 4. Normalized species concentrations vs reaction progress variable r , when water-gas-shift equilibrium constant is 0.5.

EVALUATION OF THE REACTION PROGRESS VARIABLE

We will now show that for sufficiently high temperatures the reaction progress variable, r , is equal to 1, and that this occurs at temperatures typically seen in the coal gasification cavity. The time derivative of r is given by

$$dr/dt = -(1/[H_2O]_0) d^1[H_2O]/dt , \quad (11)$$

where $d^1[H_2O]/dt$, the time derivative counting only the water consumed by reaction (1), can be written in terms of the rate constant for reaction (1):

$$d^1[H_2O]/dt = -A_1[H_2O] \exp(-T_A/T) , \quad (12)$$

where A_1 is a constant and T_A is the activation temperature, i.e., the activation energy divided by the universal gas constant.

We can calculate r by integrating Eq. (12), assuming that the value of $[H_2O]$ is determined entirely by reaction (1). This introduces some error because it ignores the consumption of water by the water-gas-shift reaction (2). Integration eliminates this error at the end points, $r = 0$ and $r = 1$. To perform the integration we must find an expression

FIG. 5. Equilibrium constant, K , for the water-gas-shift reaction, $CO + H_2O \rightleftharpoons CO_2 + H_2$.

relating the time, t , to the temperature, T . Before doing that it is convenient to transform to a new variable, $\theta = T_A/T$.

The chain rule allows us to relate t and θ :

$$dt = (dt/dx)(dx/dT)(dT/d\theta)d\theta, \quad (13)$$

with

$$dT/d\theta = -T_A/\theta^2. \quad (14)$$

The water vapor moves through the coal with velocity u , so $dx/dt = -u$. The temperature in the coal can be approximated by

$$T - T_0 = (T_s - T_0) e^{-vx/\alpha}, \quad (15)$$

where x is the distance into the coal from the surface of the cavity. This surface is at temperature T_s and regressing at velocity v . The undisturbed coal is at temperature T_0 , with thermal diffusivity α . Differentiating Eq. (15) gives

$$dT/dx = -(v/\alpha)(T - T_0). \quad (16)$$

If these expressions are substituted into the chain rule, Eq. (13), and then into Eq. (12) we get

$$\frac{d[\text{H}_2\text{O}]}{[\text{H}_2\text{O}]} = \frac{\alpha A_1}{uv} \frac{e^{-\theta}}{\theta} d\theta. \quad (17)$$

(To get a readily integrable form, T_0 in Eq. (16) was neglected in comparison to T .) Integration of Eq. (17) gives an expression for $[\text{H}_2\text{O}]$ in terms of exponential integrals which can be accurately approximated by $e^{-\theta}/\theta$ for the large values of θ appropriate to our problem:

$$\begin{aligned} \ln(1 - r) &= \ln \left\{ \frac{[\text{H}_2\text{O}]}{[\text{H}_2\text{O}]_0} \right\} \\ &= - \frac{\alpha A_1}{uv} \left[\frac{\exp(-\theta_s)}{\theta_s} - \frac{\exp(-\theta_0)}{\theta_0} \right], \quad (18) \end{aligned}$$

where θ_s is evaluated at the surface temperature and θ_0 at the temperature of undisturbed coal. The last term can generally be neglected because $\exp(-\theta_0)$ is much smaller than $\exp(-\theta_s)$.

Figure 6 shows r as a function of temperature for $T_A = 22,000$ K and $\alpha A_1/uv = 10^9$. The curve is S-shaped, nearly zero at temperatures below 1000 K, and nearly 1 at temperatures above 1300 K. Examination of Eq. (18) shows that the transition temperature depends mainly on the value of T_A . The value of the product $\alpha A_1/uv$ has little effect on the curve; an order-of-magnitude decrease merely increases the transition temperature about 100 K. The parameter values used to plot Fig. 6 were based on an experimental rate constant for reaction (1), assuming a typical characteristic length, α/v , of 1 cm and a vapor velocity, u , of 1 cm/s. The experimental rate constant was $10^6 \times e^{-22,000/T}$ grams per initial gram of carbon. Because Eq. (12) is written in terms of moles per unit volume it was necessary to divide A_1 by the density of water vapor, approximately 10^{-3} g/cm³.

Several simplifying assumptions and approximations were made in deriving Eq. (16), on which Fig. 6 is based. It is clear that these cannot affect the regions where r is close to 1 or 0, but can only affect the transition region. The errors due to the approximations are estimated to alter the pre-exponential factor by 50% or less. It is clear by examining Eq. (17) that a temperature change of a few tens of kelvins will compensate for this. So the only effect the assumptions and approximations have is to produce small changes in the shape of the transition region. This has been verified by more accurate numerical calculations.

We can now calculate the composition of the gas coming through the coal surface for any value of the surface temperature T_s . Equation (18) gives

FIG. 6. Reaction progress variable, r , vs temperature when $T_A = 22,000$ K and $\alpha A_1/uv = 10^9$.

us the value of r , and Eqs. (7)–(10) the species concentrations. We are particularly interested in the value of r at the measured cavity-wall temperatures, 1300 to 1500 K. At these temperatures r is effectively 1 and no steam passes through the coal surface into the cavity. All of the steam reacts with char to form H_2 and CO , which do enter the cavity.

CAN THE REACTION PROGRESS VARIABLE HAVE VALUES BETWEEN 0 AND 1?

Reaction (1) is endothermic by about 32 kcal/mol, so a source of heat is required to drive the reaction. Reaction (2) is nearly thermoneutral, and there are no other sources of heat within the coal, so the heat to drive the reaction must come from the gas stream in the cavity or from somewhere else in the cavity. Before looking at sources of heat it is worth noting that in general there must be surface reactions consuming part of the char.

We have been assuming steady state, which means that the drying front moves at the same velocity, v , at which the surface regresses. If the coal is ash-free or if the ash sloughs off as the carbon is consumed, the mass rate of carbon removal is $v\rho_{\text{char}}$. Similarly, the mass rate of water removal is $v\rho_{H_2O}$. Since reaction (1) involves 1 mole of H_2O reacting with 1 mole of carbon, the mass ratio of the reactants must be about 3:2; but ρ_{H_2O} is generally less than ρ_{char} . The only way that the additional char can be removed is by surface reaction with H_2O , CO_2 , or O_2 . One or more of these gases will be present at any location in the cavity, but relatively high surface temperatures are required for the reaction to occur.

The heat source which drives reaction (1) and the surface reaction may be near the surface or some distance away. If it is distant, the heat will be transported by convection or radiation. In that case the rate of heat transfer may be the limiting factor, and values of r between 0 and 1 are possible. However, such values imply surface temperatures too low for surface reaction, so the surface regression velocity will drop and steady state will no longer apply. We have not yet analyzed the non-steady-state case.

If the heat source is near the coal surface, it is most likely a diffusion flame fueled by the gases

driven out of the coal. In that case it is difficult to see how O_2 could penetrate the diffusion flame to reach the surface, so the surface temperature must be high enough for other reactions to occur if we have a steady state.

Among the more important fuels are the volatile hydrocarbons which emerge at temperatures several hundred kelvins below those required for steam/char reaction. Burning of the hydrocarbons then provides heat to drive the other reactions. This is particularly important in igniting the coal. It need only be heated to 800 or 900 K to drive off hydrocarbons, which then provide a local source of heat. However, burning the hydrocarbons does not remove carbon, so the surface must be heated to a temperature where the steam/char or CO_2 /char reaction can consume coal. Availability of steam and CO_2 should be no problem, since they are the products of the hydrocarbon combustion.

Consider now the case where r is large enough that considerable H_2 and CO are flowing through the surface of the coal. The heat of combustion of these fuels is several times the heat required to drive reaction (1), so we have a potential positive feedback mechanism. For example, if r is about 1/2 then a small increase in the rate of reaction (1) will provide additional H_2 and CO . The heat from burning this will normally increase the temperature, thereby further increasing the rate of reaction (1) and driving the system toward $r = 1$. Similarly, a small decrease in the rate of reaction (1) will set up a chain of events which drive r toward 0. Stable burning with r near 1/2 requires unusual heat transfer, such that the additional fuel results in less heat reaching the steam/char reaction zone.

Thus we conclude that, although it is possible to have values of r intermediate between 0 and 1, it is unlikely, except temporarily while reaching steady state or under special circumstances which will occur only in limited regions of the surface. This conclusion is based on qualitative arguments and needs to be made quantitative—which is the next order of business.

CONCLUSIONS

We have developed an important concept. For coal surface temperatures above about 1300 K, the gases emerging from the coal surface into the cavity consist only of H_2 , CO , and hydrocarbons. For surface temperatures below about 1000 K, only steam

and possibly hydrocarbons emerge. These two relationships have been shown rigorously. A less rigorous discussion indicates that these are the stable states. Situations where steam emerges along

with H_2 and CO can occur but are probably limited to transient circumstances or small portions of the cavity surface.

—John R. Creighton

OPERATIONAL PLAN FOR THE LARGE BLOCK EXPERIMENTS

The large block experiments were originally conceived of as a series of burn-cavity growth tests in large, isolated "blocks" of coal—in a shallow seam—that could be opened up for inspection after each burn was completed. The concept has been modified to be more economical by siting the tests side by side at an exposed coal face in a mine rather than in separate blocks in an underground seam. Although the name "large block experiments" is no longer quite so descriptive, it has been retained since it does serve to emphasize the experimental, almost laboratory, nature of the tests.

These coal gasification experiments are jointly sponsored by the U. S. Department of Energy and the Gas Research Institute. LLNL will perform the experiments in cooperation with the Washington Irrigation and Development Company (WIDCO), on whose land the experimental sites are located.

EXPERIMENTAL GOALS

The goals of the experiments are unchanged from those of the original concept. They are repeated here as updated by the supplement to the experimental plan.^{4,5} The general, overall goal is to observe the behavior of the Big Dirty coal under a variety of gasification conditions. The specific goals are as follows:

1. To determine the burn cavity shape and degree of rubble fill for a coal consumption (i.e., cavity size) of approximately 25 m³.
2. To determine the gas composition and particulate production as a function of operating conditions during the burn.
3. To observe the extent of slag formation from parting zones and coal ash and determine any interactions with the burn process.
4. To determine any significant differences in cavity growth or process behavior due to changes in steam/oxygen ratio.
5. To compare cavity growth and gas composition for an air burn and a steam/oxygen burn.

6. To investigate the interaction of the roof material with the burn process and do a preliminary test of the CRIP system.⁶

DESCRIPTION OF THE TESTS

The site for the experiments is an outcrop of the Big Dirty coal seam in the Bucoda Field of the WIDCO mine, near Centralia, Washington. Figure 7 shows the location relative to the Centralia electric power plant. A schematic view of the experimental arrangement is shown in Fig. 8.

A "drain hole"-type drilling rig will be used to drill a hole parallel to the slanted floor of the coal seam (see Fig. 9). The initial part of the slant hole will be cased and an injection liner will be inserted through the casing. This well will be used as the injection well.

A vertical hole will be drilled from above to intersect the end of the slant hole. The vertical hole will be cased to within a few feet of the point of intersection. This well will serve as the production well.

Ignition of the coal will take place at the end of the injection well liner. Oxygen/steam or air will be supplied at slightly above atmospheric pressure to minimize gas leaks. Preburn pressure and flow tests will be used to find and seal any detectable leak paths at the coal face.

The instrumentation planned for these tests is not extensive, since the major emphasis is on postburn excavation to determine the cavity shape. We will fill the burn cavities with a low-strength grout so that, on excavation, the grout cavity image can be sliced into sections to get an accurate measure of cavity shape.

The LLNL data acquisition facility will be used to monitor, process, and record all thermocouple and surface-plant data. This facility consists of a gas-sample cleanup and water-monitoring system, a gas chemistry system, an injection-flow-control station, and a data logger and computer. The

FIG. 7. Location of test site for the large block experiments.

facility is similar to that used on previous field tests,^{7,8} but with the addition of two NDIR detectors for CO and CO₂, a hot-gas chromatograph, and a new dew-point meter for analyzing water content.

The underground measurements will be limited to a number of thermocouple installations and a vertical observation well. Thermocouples will be placed in the injection, production, and observation wells as shown in Fig. 9. The observation well is designed primarily for postburn viewing of the cavity with a downhole television camera. During the burn, we intend to try a two-color infrared pyrometer at the bottom of the observation well to measure the temperature there.

Space is being made available at site 4 (see Fig. 8) for a calibration test of the HFEM system⁹

and a test of a newly developed acoustic thermometer.¹⁰

The combined roof-interaction and CRIP test has a somewhat different layout than the other tests, as shown in Fig. 10.

TEST SEQUENCE

Six experiments are planned. The first will be a practice burn to test the ignition system in a channel near the seam bottom. Four of the following experiments will be done in the main part of the coal seam just above the thickest stringer, so that they will have as nearly as possible the same stratigraphy. The remaining experiment will be

FIG. 8. Plan view of the large block experiments.

done close to the roof to insure cavity/roof interaction, and it will also be a first test of the CRIP concept.⁶

Test 1

The first experiment will test the gas ignition system and establish a short practice burn in a channel drilled as close to the seam bottom as possible to minimize leakage. This experiment will be done at location 6 (see Fig. 8). The combustion-supporting injectant gas will be air and steam/oxygen at various ratios to test the system.

We plan to use a silane-propane ignition system for these tests. Silane, SiH_4 , is a pyrophoric gas that burns immediately upon contacting oxygen. Our ignition system uses a small-diameter

gas line to inject a short burst of silane followed by a continuous propane flow. The silane ignites the propane, which then is used to ignite the coal.

Thermocouples on the propane pipe and the injection liner will be used to detect ignition of the flame. Gas analysis will determine when the coal is ignited.

This practice burn will be continued for one or two days to give an opportunity for systems checkout and some operator training. When all operations are deemed satisfactory, the burn will be extinguished and the cavity grouted up.

Tests 2-4

Tests 2, 3, and 4 will be done respectively at locations 2, 3, and 4 (see Fig. 8). They are all

FIG. 9. Typical vertical cross section for experiments 2, 3, 4, and 6.

steam/oxygen burns. These three experiments are designed to see what effects, if any, the injection flow rate and the steam/oxygen ratio have on cavity formation or product-gas composition. Neither laboratory tests nor previous field tests have shown any well-defined dependence on flow rate except for very low flow rates. The steam/oxygen ratio does seem to influence both early cavity shape and gas composition in laboratory tests, and we expect the same to be true for these tests. Also, any excess steam will tend to cool the reaction zone, which should affect the production of slag.

We would like these tests to be representative of the early stages of a large field test. Thus we have chosen the flow rate schedules so that, if continued, they would lead to a "field type" oxygen flow rate of 15 mol/s in a "fast" time of 4.5 days and a "slow" time of 12.5 days. In addition, each experiment will use enough oxygen to burn 25 m³

of coal, so that the final cavity shapes can be directly compared to see if the rate of flow increase is a controlling parameter.

The laboratory experiments we have done so far do not indicate that the form of the flow rate increase has any obvious significance. Our choice of a time-squared dependence for flow rate in these tests is somewhat arbitrary but was based on the following arguments. First, it is clear that, over some limits, flow rate should increase as the volume of the reactor increases. Certainly this is obvious if one considers the extreme case of very low flows for an enormous volume and, conversely, extremely high flows for a very small volume. Secondly, we recognize that these tests are midway in scale between small laboratory tests and large field tests, and hence that they may be useful as means of tying such tests together. We hope, ultimately, to be able to tie tests of various sizes together with

FIG. 10. Vertical cross section for experiment 5, which includes roof-interaction and CRIP tests.

our modeling effort, but currently we do not feel an adequate model is available. Consequently we have considered a simplified approach where one parameter is singled out as a candidate for scaling purposes. We can then further assume that some single value of the chosen parameter is optimum over the course of the experiment. This leads, after a number of other simplifying assumptions, to the conclusion that the flow rate should, in general, be scheduled according to $f = kt^n$, where f is the flow rate, k a constant, t the time, and n the parameter to be varied. (The exception to this power dependence for the flow rate expressions we arrived at arises with the constant-residence-time assumption, which leads to an exponential dependence on time.) This simple flow relation is attractive for three reasons. First, it allows one to prescribe a nonarbitrary flow-rate schedule for a single experiment, generally. Second, it focuses on changing a single

parameter, k , from experiment to experiment. And finally, it gives a method of scaling experiments. Our choice of $n = 2$ was a result of our feeling that, of the simple parameter values explored, the one representing constant oxygen flux per unit cavity area seemed to have the most merit, and the resulting scaling between small and large experiments seems to fit naturally within the framework of the operating experience we have had. Of course, as we gain more experimental and modeling evidence we may modify the simple $f = kt^2$ schedule.

Preliminary assignments for flow rates and steam/oxygen ratios are given in Table 10. These values were chosen partly on the basis of laboratory tests and partly to provide tests of some of our assumptions about the gasification process. They represent six possible cases, out of which we shall choose the five test conditions.

TABLE 10. Preliminary flow schedules for the large block experiments.

Case	Injected composition (steam/O ₂)	Initial flow rate (mol/s)	Maximum flow rate (mol/s)	Duration (days)	t ₀ (hr)	Value of k
Fast 1	2/1	0.25	6.0	2.6	5.0	8.6E-11 ^a
Fast 2	1/1	0.25	6.0	2.6	5.0	8.6E-11
Fast 3	Air	1.19	28.6	2.6	5.0	8.6E-11
Slow 1	2/1	0.25	3.0	4.9	14.1	1.08E-11
Slow 2	1/1	0.25	3.0	4.9	14.1	1.08E-11
Slow 3	Air	1.19	14.3	4.9	14.1	1.08E-11

^a8.6E-11 means 8.6×10^{-11} .

In Table 10, t_0 is the time required at the initial flow rate to consume the same amount of oxygen as would have been used if the flow had started at zero and increased continuously to the initial rate (according to the relation $f = kt^2$).

Test 5

The fifth test will be the roof-interaction and CRIP test at location 1 (see Fig. 8). We expect that when the burn zone reaches the roof of the coal seam, the additional heat loss will cause a deterioration in gas quality. The basic concept of the CRIP system is its ability, when such deteriorating gasification conditions occur, to move the injection point to a fresh supply of coal. The igniter is used to melt through the pipe and provide a new outlet for the injected gas, thus establishing a new burn zone upstream in fresh coal. A new cavity is started, with lower heat loss, thus restoring the gas quality to its original value.

In test 5, the new burn zone will be extinguished before it interacts with the roof, so that both stages can be seen during the excavation.

Test 6

The sixth and last test will be an air burn at location 5 (see Fig. 8). It will be done at a flow rate that gives the same oxygen flow as the slow oxygen/steam burn, so that the results from these two tests will be directly comparable.

General

Before ignition of any of these tests, the system will be leak-checked while a static pressure

is maintained in it. Freon sniffers will be used to check for surface leakage. Once the leak rate has been deemed satisfactory, the injection flow necessary for ignition will be established and the coal will be ignited. A predetermined injection flow schedule will be followed unless modifications are called for because of aberrant behavior of the system.

Each of the six experiments, except for test 1, will be run to completion (i.e., until 25 m³ of coal is consumed) and then extinguished. Steam injection followed by water flooding will be used to cool the cavity as rapidly as practical. When the cavity is cool, a downhole TV camera will be used in the observation well to try to measure whatever open cavity is visible. After the TV camera inspection, the cavity will be filled with weak cement to seal it until final excavation.

Any or all of the experimental parameters may be changed at any time. These are experiments in the true sense of the word, and we are not able to predict, with certainty, what the outcome will be.

After completing these six experiments, we should have a much better idea of the proper operating conditions for (and potential results of) the proposed Tono 1 experiment.¹¹

PREPARATION FOR THE TESTS

Hole Intersection Procedure

Each slant hole will be drilled to a length of approximately 120 ft, and the underground path of the hole plotted from data taken with a multishot

magnetic survey tool. The vertical hole will then be drilled with the objective of intersecting the slant hole. If intersection is not achieved, a gamma survey will be run, with the detector in the vertical hole and the source in the horizontal hole, to determine the distance between the holes and their orientation. If they are close enough together, final connection will be made by air pressure fracture through a packer or by well perforators. If they are too far apart, a new vertical hole will be drilled to more nearly intersect the slant hole.

Hydraulic Testing

During May and June, 1981, hydraulic tests were conducted in three holes at the site of the proposed block tests. These holes, designated 81-N-7, 81-N-24, and 81-N-25, are located as shown in Fig. 8. The natural gamma logs for all three holes and the stratigraphy for 81-N-7 are shown in Fig. 11.

Hole 81-N-7 is a 3-in.-diam cored hole whose stratigraphy is shown in Fig. 11. Before tests were conducted in this hole, a packer was set at a depth

FIG. 11. Natural gamma logs and stratigraphy for the area of the large block experiments.

of about 79 ft, so that below the packer about 5 ft of the coal seam was available for hydraulic testing. Water was introduced through a 3/4-in. PVC pipe until the pipe was full, and then the water level was monitored as it dropped. The coal seam above the packer was similarly tested by introducing water through a 2-in. PVC casing. The equilibrium water level, before and after testing, was at a depth of 67 ft. By monitoring the water level above the packer while injecting water below the packer, it was determined that an effective watertight seal had been made.

The water levels dropped very rapidly, indicating a large permeability. An analysis of the data reveals about the same coal permeability above and below the packers, of the order of 1 darcy at the location of hole 81-N-7.

After the coal seam at hole 81-N-7 had been hydraulically tested, cement grout was placed in the hole, from the bottom up to a depth of 50 ft. This then allowed hydraulic testing of the overburden, which consists of clays, siltstone, and sandstone. The clays directly over the coal have a very low permeability, perhaps as low as a few millidarcys. The sandstone and sandy siltstone are somewhat more permeable.

Boreholes 81-N-24 and 81-N-25 were drilled by the hydraulic rotary method and are 6 in. in diameter. Both were initially drilled to the top of the coal seam, then cased and grouted. The casing is steel with a 5-in. inside diameter. After the cement grout had set, the holes were extended sequentially in 5-ft increments through the coal seam. The coal was hydraulically slug-tested after each 5-ft increment was drilled. A drag bit was used for this drilling, with plain water as the drilling fluid, in order to minimize the production of fine material, which would tend to clog the pores and produce unrealistically low values of permeability.

The testing procedure was to drill 5 ft into the coal seam, remove the drilling rods, fill the casing with water, and observe the water level decay. The behavior of the water level decay indicated that the top 5 or 6 ft of the coal seam is more permeable than the rest of the seam. The value of the permeability for this upper portion of the coal seam is of the order of 1 darcy, while the lower portion has a permeability of the order of 0.1 darcy.

The results from testing hole 81-N-25 indicate a permeability of the order of 1 darcy, similar to the upper portion of hole 81-N-24. Whether the lower

portion of hole 81-N-25 is also of lower permeability cannot be determined with certainty, because the water levels were not observed for a long enough period of time. However, indications are that the water level behavior was similar to that in hole 81-N-24.

OPERATING PROCEDURE

Ignition Procedure

The coal seam will be ignited with a newly developed silane-propane igniter system illustrated in Fig. 12. Silane (SiH_4) is a pyrophoric gas that spontaneously ignites in air to form SiO_2 . It will also react with water, so all lines must be dry and leaktight.

Exact operating values will be provided for all flows and pressures. In general, the procedure is to establish an air flow of 100–200 scfm in the injection liner. Flush the igniter with dry nitrogen. Introduce a silane slug followed by a propane flow adjusted to below the flammability limit for the propane/air mixture (less than 5% propane).

It may be possible to hear the popping sound of the silane ignition, but in any case the thermocouple on the igniter should indicate the presence of a flame. If ignition fails the process is repeated.

Once the igniter is lighted, the propane and air flows are adjusted to provide sufficient heat to ignite the coal. The air may have to be enriched with oxygen at this stage to provide enough heat.

When satisfactory coal ignition has been achieved, as determined by gas composition measurements, the propane flow will be stopped and the igniter retracted a short distance into the injection liner to protect the tip from damage during the gasification phase of the experiment.

Optical Pyrometer

A two-color infrared optical pyrometer will be used to measure the temperature at the bottom of each observation well after the cavity has developed sufficiently to reach that point. (Since the observation well bottoms out 4 ft above the slant injection hole, no pyrometer measurements will be possible until well into the burn, when the cavity has expanded about 4 ft vertically.) This pyrometer has a range of approximately 900–2000°C.

FIG. 12. Silane/propane igniter and pipe cutter.

The observation wells will be equipped with fused quartz windows and nitrogen purge systems so that visual observations can be made. Periodic checks will be made with the TV camera to visually observe the cavity intersection. Once intersection occurs, pyrometer measurements will be made at hourly intervals.

Particulate Emission

At the planned flow rates, velocities in the incinerator are low enough so that particulate emission from the incinerator should not be a problem. However, fine particulates could still be emitted. If large quantities of particulates are found, the flow rate will be reduced as a control measure. If the situation persists, some experimentation will be done with flow rate variations to try to determine the relationship, if any, between particulate volume and flow rate.

We will keep a photographic record of incinerator stack emission on a twice-daily basis, and more often if particulate excursions take place. A title sign will be used to record, on the photograph, the time and other pertinent information.

TV Inspection of Burn Cavities

A downhole television camera will be used with a tape recorder to inspect and record any open cavity left after each burn zone has been cooled. The camera will be lowered down the observation well. If needed, a nitrogen flush line will be used to keep the well clean.

We expect that some free-standing cavity will remain after water cooling is completed and that visibility may be sufficient to make reasonable observations. It will probably be necessary to provide an air lift or water jet pump to remove the water from the cavity before the inspection, because the water will likely be too dirty to see through. Some storage facility for this dirty water will be needed.

The sound channel on the tape recorder will be used for real-time voice recording of depth, direction, and other pertinent information.

After visual inspection has been completed, the burn cavity will be filled with low-strength grout to preserve the cavity shape for final excavation and measurement. The grout will also help to seal each experiment from the adjacent ones.

Excavation Procedure

The final operation associated with the tests will be the excavation of the burn zones to obtain first-hand measurements of their size and shape. The direction of overburden removal will be from the injection wells at the face of the coal seam toward the production wells. The order in which the tests are excavated is not critical.

Overburden disposal will be at the direction of the mine operator, as will disposition of the portion of the coal seam that is removed.

Dimensional data will be taken at intervals necessary to produce an accurate representation of the cavity shape. Cavity dimensions to within about 6 inches will be adequate.

—R. W. Hill
D. S. Thompson
C. B. Thorsness

SITE CHARACTERIZATION OF THE PROCESS ZONE FOR TONO 1

A general site in the Tono Basin near Centralia, Washington, was chosen by DOE for the next *in situ* coal gasification tests. The site was surveyed and partially characterized by a team led by Sandia National Laboratories, Albuquerque,¹² and the results were used in selecting a specific location for the Tono 1 gasification test. The coal seam at this location is apparently free of faulting.¹³

Although only a minimal hydrology program was included in the site characterization effort, the testing of the wells that were completed showed that the Big Dirty coal seam has a low permeability, of the order of $0.025 \mu\text{m}^2$, and that the siltstone above the coal has a very low permeability.

Further testing on well H-2 in July 1981 showed it to be a weakly flowing artesian well with an average long-term flow rate of 2 liters per hour. There is some methane in the coal seam which escapes through the water in the well. No measurements were taken of the gas flow rate.

Standard well-testing methods were used to analyze the data from a test on this well. The results indicate a very small permeability of about 0.1 millidarcy ($0.001 \mu\text{m}^2$) and a relatively large storage coefficient of about 0.02. This large storage coefficient indicates a "soft" aquifer (one that is relatively compressible), a condition due in part to the methane gas which coexists with the water in the coal seam.

The combination of small permeability and large storage coefficient means that the hydraulic effects of flow from a well do not propagate very far from the well. For example, a well can be as close as 12.5 ft to another well that is being

pumped and yet not experience significant drawdown until after 60 days of pumping. Thus cross-well pumping and drawdown tests are not a practical test method for this site.

Since the tests done to date have shown no significant aquifers in or above the coal seam of interest, a very simple hydrology plan is indicated for the Tono 1 experiment. The emphasis of the plan is nearly equally divided between geologic structure definition, hydrologic testing of the coal and overlying strata, and water sampling for monitoring purposes.

Three hydrologic test wells are planned as shown in Fig. 13. Wells W-1 and W-2 are each 100 ft from the proposed directionally drilled injection well, and all three wells form an equilateral triangle with a 200-ft side.

The wells will be drilled through the Big Dirty seam to a depth of about 600 ft. Each well will be cored through the coal seam, with coring starting in W-1 at a distance of 30 ft above the coal seam. Top and bottom coal elevations will be determined from the core data. A composite coal sample from each core hole will be saved for chemical analysis.

The wells are to be drilled by the hydraulic rotary method, using plain water as the drilling fluid if possible. (The WIDCO mine driller should be consulted about the drilling of these wells, because he may have helpful suggestions on achieving the desired objectives.) If drilling mud is required, REVERT should be used and the well should be flushed with plain water after drilling. After coring is completed, the wells can be reamed to a final diameter large enough for the installation

FIG. 13. Map showing planned locations of the three hydrologic test wells—W-1, W-2, and W-3—at the Tono 1 experiment site.

of the samplers. Consultation with the BARCAD* engineer will be necessary to choose this diameter.

The well will be completed as shown in Fig. 14, with BARCAD water samplers installed at several levels. A schematic of these samplers is shown in Fig. 15 to illustrate the operating method. For low-permeability formations such as this one, they can be used to perform minislug withdrawal tests and as bubblers for water level determinations.

After the hydrology testing has been completed, the wells will be used for water quality monitoring.

A hydrophone will be placed in each well near the bottom of the coal seam. Later, during the directional drilling program, the hydrophones will be used to listen for the sound of the drill bit, as a possible aid in establishing its location.

Each well will provide five levels for measurement. These levels represent the strata that are of most potential interest hydrologically. The levels are far enough apart to allow good isolation between samples.

*BARCAD Systems, Inc., P.O. Box 424, Concord, MA 01742.

—R. W. Hill
W. A. Murray (Consultant)

FIG. 14. Plan for completion of well containing BARCAD water samplers.

- (1) Initial condition: (2) Apply N_2 pressure, force stagnant H_2O down outer tube and up inner tube to waste. (3) Maintain N_2 pressure until all H_2O is removed from tubing. (4) Vent tubes, valve opens. Fresh H_2O from formation flows into sampler and up tubes, displacing stagnant H_2O (see (5) below).
- (5) Repeat steps 2, 3, and 4; H_2O is forced out of tubing and replaced with fresh formation H_2O . Repeat several times to insure complete removal of stagnant water. (6) Repeat steps 2, 3, and 4 and collect sample.

Stagnant water
Fresh formation water
 *Patent pending

FIG. 15. Schematic diagram showing operation of a BARCAD water sampler.

POSTBURN DRILLING RESULTS FROM HOE CREEK 3

The general objective of the Hoe Creek 3 experiment was to improve our understanding of the geological factors affecting the underground coal gasification process and establish the extent to which the geology of the site affects the process. To achieve this general objective, a core drilling program was implemented at the Hoe Creek 3 site about ten months after the conclusion of the burn experiment. This report summarizes preliminary interpretations and conclusions derived from the exploratory coring program.

The objectives of the postburn drilling program were: (1) Determine the configuration of the burn cavity. (2) Sample the materials found within the burn cavity. (3) Establish the degree of thermal alteration induced in the earth materials surrounding the burn cavity by the high temperatures associated with the burn. (4) Assess the effectiveness of the horizontally drilled link borehole and the impact it had on the configuration

of the burn. (5) Obtain information on the extent and characteristics of the collapsed region.

A series of 16 exploratory boreholes were drilled. Figure 16 illustrates the positions of these holes relative to the experiment axis and the injection and production wells. Twelve of the holes were drilled vertically, three were at inclined angles, and one was a reentry of the injection well P-1. The inclined holes were drilled to avoid areas where surface subsidence had occurred or where the probability of additional surface subsidence was significant. Coring typically began once drilling fluid circulation was lost.

One major objective of the Hoe Creek 3 experiment was to achieve forward gasification through a known reliable linking channel near the bottom of the coal seam. To construct this channel, a deviated borehole was drilled from the surface to horizontally connect the injection and production wells through the coal near the bottom of the

FIG. 16. Plan view of the Hoe Creek 3 experimental layout, showing the positions of the postburn exploratory core holes relative to the process wells.

Felix 2 seam. The linking portion of the hole was drilled parallel to and approximately 10 ft above the lower contact of the Felix 2 seam. We show in the cross sections included that the linking channel can have a significant effect on the underground burn process.

The geology of the Hoe Creek 3 site had a major impact on the development of the burn cavity and on the burn process. Figure 17 illustrates the relative positions and the absolute thicknesses of the geologic units present at Hoe Creek. The upper 84 ft consists of interbedded sandy siltstones and silty claystones which represent lacustrine depositional environments (lake environments). Below these lacustrine deposits is a sequence of relatively clean (i.e., containing very little silt or clay) and permeable sands which extend from approximately 84 ft down to 129 ft. These sands were probably deposited along ancient river channels. The Felix 1 coal is below this unit and is approximately 11 ft thick. A rock split sequence separates the Felix 1 and Felix 2 coals. This sequence consists of the Felix 1 underclay, a sand lens, and the Felix 2 claystone cap rock. The Felix 2 coal underlies the rock split sequence and is approximately 24 ft thick.

FIG. 17. Simplified geologic section of the Hoe Creek 3 site, showing relative positions and thicknesses of the various geologic units.

It is important to note that all the earth materials previously described are poorly indurated. They are generally weak or friable, with strength characteristics very similar to those expected from soil materials, and are likely to be unstable if they form the roof and sides of an underground cavity. This instability will tend to be aggravated by the drying, slaking, and cracking induced by the high temperatures of the burn. The channel sands can be particularly unstable as a result of their cohesionless characteristics. In addition, they have significant permeability because their silt or clay content is very low. This layer would probably permit fluids to move into or out of the cavity with ease.

Two weeks after the experiment ended, subsidence of the ground surface occurred. Gradual collapse of the roof continued after the completion of the burn as the roof of the cavity migrated upward. Materials overlying the roof became unstable and surface subsidence developed.

Three sets of cross sections present our interpretation of the cavity characteristics. The first set (Figs. 18–22) gives simplified cross-sectional interpretations of the cavity characteristics immediately after the last day of the burn. The second and third sets (Figs. 23–25) show cross sections of the cavity and underlying collapsed region ten months after the burn ended, when surface subsidence had occurred and the postburn core drilling was done. Figures 23 and 24 are simplified cross sections illustrating the cavity characteristics, while Fig. 25 is a three-dimensional cross section (fence diagram) illustrating the distribution of the materials recovered from the core holes. Figure 25 serves to summarize some of the detailed data used to construct the simplified cross sections of Figs. 18–24.

The results obtained during the postburn coring activities have provided useful information on the various characteristics of the burn cavity and surrounding materials. The conclusions derived from this study are:

1. The overriding tendency of the hot gases within the cavity had a significant impact on the size and shape of the cavity. Figures 19–21 show that the bottom and sides of the cavity were bowl-shaped. Figure 22 shows that the lateral extent of the burn was greater in the Felix 1 seam than in the Felix 2 seam as a result of this tendency.

2. Significant roof collapse occurred during the burn. The cavity materials which probably

represent this collapse are the highly thermally altered rubble and partially melted materials such as fused sandstones, breccias, glass, and slag (see Figs. 18–21). A smaller volume of material also fell from the rock split sequence which separates the Felix 1 and Felix 2 seams. As a result of the gradual collapse of the roof, significant heat losses occurred which affected the gasification process.

3. The horizontally drilled link channel (DD-1) effectively controlled the margins of the cavity and the direction of the burn. Figures 18–21 show that very little coal burned below the level of DD-1. In addition, Fig. 22 suggests that the cavity was approximately axisymmetric relative to the experiment axis due to the presence of DD-1.

4. The upper margins of the Felix 2 coal present at the bottom of the cavity generally exhibited very little evidence of thermal alteration. The slag apparently acted as an insulation blanket which protected the Felix 2 coal from the high temperatures induced by the burn.

5. The outline of the cavity in plan view has the shape of a teardrop (see Fig. 22). In vertical transverse cross section, the cavity outline is mushroom-shaped (see Figs. 19–21).

6. The channel sand sequence overlying the burn cavity suffered slight thermal alteration, which was probably induced by the movement of hot gases throughout this permeable unit. This

zone of alteration is shown in Figs. 18–21.

7. Gradual collapse of the roof occurred during the course of the burn and later. As a result, much of the material fell into the cavity as blocks, and numerous voids were formed. The bedding planes of many of the blocks were not oriented horizontally, indicating that the blocks had rotated in falling. This fact suggests that the blocks were small relative to the size of the cavity.

8. Material that collapsed into the burn cavity after the end of the experiment is mostly very weak and contains an abundance of voids. A void zone was found near the bottom of this region (see Fig. 25). This void zone may continue to migrate upward, but the bulking of the overlying materials fragmented during the process will tend to gradually backfill the voids. Figures 23 and 24 show that a zone of fractures and/or strain-softened materials in the uncollapsed roof and walls immediately overlying the collapsed region tend to be oriented somewhat parallel to the upper margins of the collapsed region. Fluid level measurements obtained immediately after the boreholes were drilled suggest that there is good hydraulic connection between the different zones of the burn cavity.

—A. Ramirez
D. Wilder

FIG. 18. Longitudinal vertical cross section through Hoe Creek 3, showing an interpretation of the burn cavity as it was immediately after the experiment ended.

FIG. 19. Transverse vertical cross section through Hoe Creek 3 at injection well P-1, showing an interpretation of the burn cavity as it was immediately after the experiment ended.

FIG. 20. Transverse vertical cross section through Hoe Creek 3 at a point midway between injection wells A and P-1, showing an interpretation of the burn cavity as it was immediately after the experiment ended.

FIG. 21. Transverse vertical cross section through Hoe Creek 3 about halfway between the injection and production wells, showing an interpretation of the burn cavity as it was immediately after the experiment ended.

FIG. 22. Plan view showing the margins of the Hoe Creek 3 burn cavity in the Felix 1 and Felix 2 coal seams.

FIG. 23. Longitudinal vertical cross section through Hoe Creek 3, showing an interpretation of the burn cavity and collapsed region as they were at the time of postburn core drilling.

FIG. 24. Combined transverse vertical cross section (B-B' and D-D') through Hoe Creek 3, showing an interpretation of the burn cavity and collapsed region as they were at the time of postburn core drilling.

FIG. 25. Fence diagram, showing a three-dimensional view of the Hoe Creek 3 subsurface conditions at the time of postburn core drilling.

U. S. PATENTS GRANTED FOR SOVIET UCG PROCESS TECHNOLOGY

Since 1976 the Soviets have been granted four U. S. Patents dealing with various aspects of the underground coal gasification (UCG) process.¹⁴⁻¹⁷ Two of these patents concern linking, one concerns processing of channels, and one concerns optimization of the gasification process.

The techniques involved in three of these patents are either described in the open Soviet literature on underground coal gasification or are based on logical extensions of techniques described in the literature. The one exception is hydraulic fracture linking (U. S. Patent 3,990,514), which is

not described in the UCG literature. Whether the Soviets ever made extensive use of this technique is not clear.

It is instructive to examine these patents to see which of the many features in the complicated UCG process the Soviets felt were worth patenting. Also, a careful reading of these patents provides some insight into changes which have occurred since 1968, when the Soviets stopped reporting UCG details. In the following sections, each of the four patents is described briefly and techniques of special interest are cited.

METHOD OF CONNECTING WELLS

U. S. Patent 3,990,514—Kreinin, Fedorov, Antonova, Volk, and Gershevich (Nov. 9, 1976; filed June 11, 1975).

This patent concerns a method of hydraulic fracturing which allows directional control of the desired links. When two holes are to be linked, e.g., holes 3 and 2 in Fig. 26, air is blown into one of the holes, say hole 3, and hole 2 is shut in. All other holes with which 3 is not to be connected are left open. Water under a pressure equal to the overburden pressure plus the fracture strength of the coal bed is then pumped into well 3. When the pressure in well 2 rises to this value, the valve at well 2 is immediately and instantaneously opened. The ensuing pressure drop results in a hydraulic shock which breaks up the coal by expanding the fissures.

Water is continuously pumped in after the holes are linked to increase the diameter of the gasification channel until it will accommodate a flow rate of 1000 to 2000 m³/hr at a pressure of 2–5 atm. In this phase the water flow is maintained at a rate sufficient to carry broken pieces of coal to the surface. After the connection between wells 3 and 2 is completed, an air flow (at a pressure less than that of the water being pumped in) is maintained in order to keep this link open while successive pairs of holes are similarly linked; e.g., 4 to 3, 5 to 4, etc. (At one place in the patent it is stated that the link is maintained with a small *air* flow; at another place it is stated that the link is maintained with a small *water* flow.)

When all of the wells are linked, e.g., 9 through 2, air at a pressure greater than that of the remaining water is introduced into well 9 and expelled from well 2. In this fashion the system is purged of water and the channel further widened.

FIG. 26. Plan view of a portion of a gas generator showing holes to be linked.

This patent includes operating parameters for two specific links carried out for holes 20 to 30 m apart in a seam 235 to 238 m deep, 1.6 to 2.0 m thick, and sloping 25° to 55°. The overburden pressure was 60–65 atm and the fracture strength was 20 kg/cm², for a total hydraulic fracturing strength of 80–85 atm. However, due to a significant loss of pumping liquid which flowed out of the open wells, an operating pressure of 100–110 atm was used with a flow rate of 0.08 to 0.1 m³/min at the source well. After two hours, the flow rate rose to 0.4 m³/hr in well 3 and the pressure fell to 80 atm; in well 2 the pressure rose to 60 atm. Immediately after well 2 was opened, the pressure fell to 1 atm gauge and the water pumped in at well 3 flowed out at well 2 with no loss to the formation. This link was then flushed extensively with water for 1-3/4 hr. Finally, the link was purged with air at 28 atm pressure until the wells permitted an air flow of 4800 m³/hr.

Next, well 3 was shut in and water was pumped into well 4 at 100 atm and 0.2 m³/min. The link between wells 3 and 2 was maintained by a water flow of 1.5 m³/min pumped into well 2. After 2 hours the pressure fell in well 4 to 76 atm and rose in well 3 first to 35 atm and then to 56 atm while the corresponding flow rates increased to 0.5 m³/min and then to 0.7 m³/min. The link between 4 and 3 was flushed for 2.5 hr, after which 3 was sealed, and the link from 4 to 3 to 2 was flushed. Finally, this link from 4 to 3 to 2 was flushed with high pressure air.

It was stated in this patent that the injection and exhaust wells should be cased through at least two-thirds of the seam, and that the uncased portion should not exceed 2 m. In this way the hydraulic fracture would lie as close to the bottom of the seam as possible, a desirable feature because "should the hydraulic-fracturing fissure be formed in the upper portion of the coal bed, the coal underlying this fissure would remain ungasified."

METHOD OF PROCESSING COAL CHANNELS IN UNDERGROUND COAL GASIFICATION

U. S. Patent 4,024,914—Kreinin (May 24, 1977; filed Nov. 19, 1975).

Although the method described in this patent presumably applies to all drilled channels in all coal

types and seam contours, the diagrams are for steeply dipping beds, and the experiments were carried out in hard coal at Yuzhno Abinsk. The channel to be processed is heated rapidly (80 to 100°C per hour) to at least 500°C by blowing hot gases through it at a rate between 1500 and 2500 m³/hr. A pressure slightly above hydrostatic pressure and a temperature of at least 500°C are maintained throughout the processing period, which lasts 15 to 20 days. After that time the pressure is reduced to 0.4 to 0.8 atm and the flow rate is increased for gasification. Although this method of processing is especially advantageous in swelling coals, it is also beneficial in all coal channels.¹⁸⁻²⁰ (The authors feel that water inflow, for example, can cause channel blockage.) According to a reference cited in the patent: "Operation of a coal channel whose walls have already been coked is substantially facilitated (Proceedings of All-Union Research Institute of Gas Industry, No. 8, pp. 91-95, Gostechizdat Publishers 1962)."* In contrast to various articles in the literature which specify the required diameter,²¹ for example, or the amount of coal to be gasified in a countercurrent combustion step,¹⁸⁻²⁰ this patent describes the channel temperatures necessary to ensure proper operation of the gasification process. Reference 22 indicates that the overpressure technique described in this patent is used routinely today.

COUNTERCURRENT COMBUSTION (CCC) LINKING†

U. S. Patent 4,036,298—Kreinina and Zvyagintsev (July 19, 1977; filed Aug. 12, 1975).

This patent covers linking of successive holes. It suggests that when several adjacent holes are to be linked (holes 2 through 9 in Fig. 26, for example), a combustion zone might be started at hole 2, for example, and an air blast injected at hole 3 at a pressure of 32 atm and 1100 m³/hr. When the pressure at hole 3 has dropped by 20 to 25% (if the coal permeability is 0.05 darcy), or by 40 to 50% (if the permeability is 1 darcy), air injection should be started at hole 4. When the pressure in hole 3 drops

to 1 or 2 atm, indicating that a link has been formed to hole 2, the flow rate in hole 3 is increased to 3200 m³/hr, and while linking continues (between 4 and 3) gasification begins (between 3 and 2). Air blast at 30 atm and 1100 m³/hr continues in hole 4 until the pressure drops 25% (or 50%), at which point blast is initiated in hole 5, etc. In this fashion a continuous link can be formed from hole 2 to hole 9.

The patent does not address the issue of where a link might form, e.g., in a circuitous path from hole 2 to hole 3, along the coal seam roof, etc.

There are a few incidental pieces of useful information contained in the patent application:

1. The holes were linked using a constant flow rate, the choice of which depended on the hole separation. It was suggested that for a separation of 20 m the flow rate should not fall below 200-300 m³/hr.

2. The linking rate was expected to be 2.1 m per day.

3. The hole separation for which the patent was written was 19.5 m.

4. When the link is established and the pressure drops, water inflow will increase and may move the combustion front away from hole 3 back toward hole 2.

5. When the gasification blast is first introduced into hole 3, the large rush of air may also displace the combustion focus toward hole 2.

METHOD OF UNDERGROUND GASIFICATION OF A COAL BED

U. S. Patent 4,083,402—Antonova and Kreinina (April 11, 1978; filed Feb. 17, 1976).

The underground coal gasification method discussed here involves careful drying and predrying of the gasification area and careful regulation of the gasification rate in order to maintain stable production of product gas with the desired heating value.²⁴ All diagrams refer to steeply dipping beds, although the technique presumably would be applicable to flat seams as well. An efficiency factor of at least 0.6 (energy recovery) is assumed. It is stated that if the water flow in the gasification zone exceeds 3 m³/hr, "it is quite difficult to control the process to maintain the rate of gassing out of the coal." (If necessary, the gasification generator should be predried and continuously dried during

*See *Nauch. Trudy VNII Promgaz*.

†A complete discussion of CCC linking is found in Ref. 23.

gasification to maintain this level.²⁵⁻²⁷) A formula is postulated which relates the required coal gasification rate (I) with the desired heating value Q_L^g and with various natural factors:

$$I = \frac{W F^{1.9}}{0.506 m^{0.702-0.659F}}$$

where

I = intensity of the process, i.e., amount of coal gasified per unit time (tons/hr)*;

W = amount of water flowing into the gasification zone (m^3/hr);

$$F = \frac{Q_L^g V}{Q_L^c};$$

Q_L^g = the lower heat of combustion of the gas (kcal/ m^3);

V = the yield of gas from 1.0 kg of coal (m^3)*;

Q_L^c = the lower heat of combustion of the coal (kcal/kg);

m = the thickness of the coal bed (meters).

Note that Fig. 27 differs from the previous rendition of this figure as seen in Ref. 20 (four wells for predrying the coal are included).

*In the USSR, 1.1 m^3 of blast is generally required to produce 1 m^3 of product gas.

*This was typically 2.8 m^3 for the lignite gasified at Angren, and 4.2 m^3 for the bituminous coal gasified at Yuzhno Abinsk.

FIG. 27. Plan view of an underground gasification generator in a steeply dipping bed.

CONCLUSIONS

The Soviets have been gasifying coal *in situ* for nearly 50 years; details of experiments carried out during the first 35 years are available in the literature. Nevertheless, over 40 U. S. Patents in the field of UCG have been issued since 1970. Many of these patents relate to techniques not used in the USSR. There are a few, however, such as those reviewed here, which cover basic techniques

described repeatedly in the literature; e.g., casing process wells through the overburden,²⁸ inclined horizontal linking,²⁹ dewatering,³⁰ and the use of different gas pressures to control water inflow.³¹ These patents may become important whenever the UCG process is commercialized in the U. S.

—D. U. Olness

ABSTRACTS OF REPORTS COMPLETED THIS QUARTER

The Podmoskovnaya Underground Coal Gasification Station

D. U. Olness.

UCRL-53144 (75 pp.).

This report continues our survey of the Soviet effort in underground coal gasification and summarizes research conducted at the Podmoskovnaya Station until its close in 1963. Techniques for *in situ* coal gasification without using underground labor to create the necessary channels were employed. Countercurrent combustion linking, electrolinking, hydraulic fracturing, and inclined horizontal drilling were among the linking methods applied to the relatively flat seams of lignite found near Tula. By the late 1940s, improvements at the Podmoskovnaya Station enabled the Soviets to operate the facility primarily as a small industrial station. This report discusses the geological, hydrological, chemical, technological, and economic factors affecting construction, process optimization, operation, and maintenance of *in situ* generators. Available data for individual generators operated at the Podmoskovnaya Station are also presented.

Proceedings of the Seventh Underground Coal Conversion Symposium

D. R. Stephens, Symposium Chairman.

CONF-810923.

This symposium, hosted by LLNL at Fallen Leaf Lake, Calif., Sept. 8–11, 1981, drew an international list of participants. Sixty-nine papers were

presented, including nine from LLNL. Abstracts of the LLNL papers are given below.

"Postburn Core Drilling Results from Hoe Creek 3"

A. L. Ramirez, H. C. Ganow, and D. G. Wilder.
CONF-810923 (pp. 29–40).

This paper presents interpretations derived from the analysis of the postburn drilling results from the Hoe Creek 3 experiment. Sixteen partially cored boreholes were drilled using an HQ triple-tube core barrel. The general objectives of this work were to establish the characteristics of the burn cavity and of the materials within and surrounding the cavity. The lateral extent of the burn and the characteristics of the collapsed region overlying the burn cavity were also to be investigated. Important conclusions derived from this study include the following: (1) The horizontally drilled link borehole strongly controlled burn cavity shape and location; no significant combustion occurred below the link. (2) The slag may have acted as an insulation blanket, protecting the coal below the horizontal link borehole. (3) Significant roof collapse occurred during the course of the experiment, probably inducing substantial heat losses. (4) The lateral extent of the burn was greatest along the Felix 2 seam. The cavity outline in plan view is shaped like a teardrop; a vertical transverse cross section through the cavity shows a mushroom-shaped outline. (5) Roof collapse after the end of the experiment filled much of the space within and above the cavity, producing a mechanically disturbed zone full of voids and

weak materials. A zone of fractures or loosened material exists in the remaining (uncollapsed) roof and wall materials, surrounding and paralleling the upper margins of the collapsed region. A void zone was found near the bottom of the collapsed region.

"Burn Cavity Growth During the Hoe Creek No. 3 Underground Coal Gasification Experiment"

R. W. Hill.

CONF-810923 (pp. 41-65).

A detailed history is given of the growth of the burn cavity during the first month of the Hoe Creek No. 3 underground coal gasification experiment near Gillette, Wyoming, in 1979. The changing shape of the cavity with time is inferred from data from three types of instruments installed throughout the experimental zone: (1) thermocouples at various levels in a number of holes, to map temperatures; (2) extensometers at various levels in other holes, to detect motions of the overburden material; and (3) high-frequency electromagnetic (HFEM) scans made between various pairs of holes, to detect cavities and zones of burning coal. Additional data on the final shape of the underground cavity is derived from the results of a core drilling program carried out from the surface after the burn had ended. This study of cavity growth history has contributed significantly to our understanding of how the *in situ* coal gasification process operates in sites like Hoe Creek.

"Effects of Gas Flow Pattern on Cavity Shape"

J. R. Creighton.

CONF-810923 (pp. 199-212).

The effects of different gas-flow patterns on the cavity shape in laboratory-scale coal block experiments are shown. For simplicity, the burning of pure carbon rather than coal is modeled. The rate of removal of carbon from the cavity wall is shown to depend on the local rate of oxygen transport to the wall. A numerical model which assumes plug flow in the cavity with a laminar boundary layer gives cavities shaped like an exponential horn, with the largest radius next to the inlet. The downstream shape is in reasonable agreement with experiment but the upstream shape differs. When the flow in the cavity is calculated using the full Navier-Stokes equations, the flow near the inlet resembles an expanding jet surrounded by a toroidal vortex. The

maximum rate of oxygen transport to the wall occurs where the jet strikes the converging cavity wall some distance downstream. The reduced oxygen transport near the inlet causes the upstream portion of the cavity to be rounded, in agreement with experiment. The downstream portion of the cavity is similar to that with plug flow.

"Coal Block Gasification Experiments: Laboratory Results and Field Plans"

C. B. Thorsness and R. W. Hill.

CONF-810923 (pp. 331-351).

The inability to visually inspect *in situ* gasification cavities has hindered our understanding of the process. As a step in overcoming this problem, laboratory-scale steam/oxygen gasification experiments have been performed in 300-kg coal blocks in which the initial gasification channel was a small drilled hole. At the end of the experiments the cavities were examined. For the three coals studied (Wyodak, Hanna, and WIDCO), the cavities were quite different, yet the product-gas heating values were similar. Detailed results of these tests are presented. Concern over the ability to scale small experiments to a large field system led to a proposal to perform intermediate-scale tests at an exposed coal face. The test plan for the first of these tests, to be performed at the WIDCO mine site, is outlined.

"Designing Process Wells for an Underground Coal Gasification Environment"

D. S. Thompson.

CONF-810923 (pp. 461-480).

Recent large-scale field experiments designed to advance the state of underground coal gasification (UCG) technology have forced the recognition of some critical uncertainties associated with the UCG process. Among the most important of these uncertainties occurs in attempting to define the reaction zone geometry. Batch processing of a flat-lying coal seam between two process wells involves complex flow patterns, any number of separate reaction zones, and interactions with surrounding media. All of these factors have significant impact on the overall efficiency of the UCG process, and all of them in turn are strongly affected by success or failure in maintaining the integrity of the process

wells. The reasons why process well integrity is so important are covered here in a review and evaluation of significant data generated from various field tests, including identification of well failure mechanisms. We observe a close relationship between process well behavior and process performance, which leads us to conclude that reliable process-well performance is critical in establishing and maintaining control over the UCG process. As a logical extension of this evaluation, we develop design and performance criteria for UCG process wells. Applications to the next generation of field tests are presented in the form of proposed design features for UCG process wells, features intended to prevent the failure modes that have occurred in past field experiments.

"Groundwater Contamination Near the Hoe Creek UCG Experiments"

F. T. Wang, S. W. Mead, and D. H. Stuermer.
CONF-810923 (pp. 619-640).

It has been shown that underground coal gasification (UCG) may introduce a broad range of residual gasification products into the groundwater of a coal aquifer. Sorption of many contaminants by the coal itself is an important factor in restricting the migration of these contaminants in the groundwater. However, our field studies, conducted at LLNL's Hoe Creek site, have shown that sorption of organic compounds by coal is not as effective as expected, perhaps because the coal surface area is limited. Furthermore, if severe roof collapse has taken place during gasification, non-coal aquifers located above the gasified coal seam may be interconnected with the coal aquifer, and contaminants may enter these non-coal aquifers, in which sorption is even less effective. The Hoe Creek 2 and 3 experiments have provided us with opportunities to study the contamination of a sand aquifer located above a gasified coal seam in a hydrological recharge area. Our preliminary results indicate that the water in the overlying sand aquifer is much less contaminated with organic compounds than the water in the gasified coal aquifer. In conducting these field investigations, we have also learned

valuable lessons concerning groundwater monitoring. A suggested monitoring strategy is discussed.

"The Controlled Retracting Injection Point (CRIP) System: A Modified Stream Method for *In Situ* Coal Gasification"

R. W. Hill and M. J. Shannon.
CONF-810923 (pp. 730-737).

The underground coal gasification process, in practice, is subject to various problems that make it difficult to maintain and control an efficient long-term operation. One of the major problems is the need to move the injection point (where the combustion-supporting air or oxygen from the surface is fed into the coal seam) to new areas of unburned coal as the burn progresses. To achieve better control of the gasification process, we recommend the controlled retracting injection point or CRIP system. With this technique, the operator can choose the optimum time and distance to move the injection point, and consequently the burn zone, to get the best possible performance from the gasification process.

"Soviet UCG Experience Specifically Related to Field Experiments in the United States"

D. U. Olness.
CONF-810923 (pp. 823-828).

During the past eight years, some 20 underground coal gasification experiments have been conducted in the United States. Most of these experiments produced gas with a heating value in excess of 100 kJ/mol, but various problems have prevented the achievement of ideal results. For example, at Hoe Creek there were problems with hole failure and override, and at Hanna some of the reverse-burn links either lay higher in the seam than was anticipated or required an excessively long time for completion. Publications describing over 35 years of experience in the Soviet Union reveal that the difficulties encountered in the United States have occurred in the Soviet Union as well. This report discusses the Soviet experience with problems similar to those observed in the United States.

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