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C. B. Thorsness
R. W. Hill

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COAL BLOCK GASIFICATION EXPERIMENTS: LABORATORY RESULTS AND FIELD PLANS*

C. B. Thorsness and R. W. Hill
Lawrence Livermore National Laboratory, University of California
Livermore, CA 94550

ABSTRACT

The ability 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 of 300-kg coal blocks were performed using an initial drilled link. 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 intermediate-scale tests, to be performed at the WIDCO mine site, is outlined.

INTRODUCTION

The process of in situ coal gasification is difficult, if not impossible, to observe in detail. How the growth of the gasification cavity influences and is influenced by injected gas composition, flow rate, and coal type is not well understood. This difficulty is in large part a result of our lack of detailed knowledge about the nature of the developing gasification cavity. Generally in field tests only remotely available data (e.g. thermocouple) are available, and often these data are ambiguous. The ability to visually inspect burn cavities would considerably aid our understanding. In the few cases where well documented excavation of a burn cavity has been done, a better understanding of the course of the test is available.[1]

We will always be limited by economic considerations in studying relationships among process variables and their interaction with a developing gasification cavity. Field tests (especially excavation of field tests) are too expensive to permit the study of many variables. One solution is to use small-scale tests to study process interactions and then to extrapolate information to the field.

When small tests simulate large-scale phenomena, problems arise from the difficulty of scaling all the important physical and chemical processes. Since it is generally impossible to correctly scale all processes, small-scale tests may not be true simulations of large-scale behavior. Gasification is a result of complicated interactions (e.g. fluid flow, heat transfer, mass transfer, chemical reactions, and mechanical and thermal alterations) and, as such, the problem of scaling is severe. For example the mechanical spalling of material is certainly a length-scale dependent phenomena and is probably not well represented in small-scale experiments. The relative importance of radiant and conductive heat transfer as well as forced and free convection are undoubtably poorly represented. However, the ability to observe gasification cavities and the relative economy of small-scale laboratory tests still make them attractive. As a result, we have conducted a number of laboratory tests to determine initial cavity shape as a function of coal type.[2,3] Recently we conducted more complete tests in which most of the important process variables were monitored.

In preparation for a future full-scale field test and as an initial attempt to address some of the scaling problems, we have been planning the first in a series of intermediate-scale tests. The first tests will consist of 6 small gasification experiments in an exposed coal face at the Washington Irrigation and Development Company (WIDCO) mine near Centralia, Washington.

In this report we first describe the results of our most recent laboratory-scale tests. These include the gasification (with a steam/oxygen mixture) of three coals: Hanna coal from the Arch Mineral Seminoe No. 2 mine near Hanna, Wyoming; Wyodak coal from the Kerr-McGee Jacob's Ranch mine near Gillette, Wyoming; and WIDCO coal from the Big Dirty seam of the WIDCO mine near Centralia,

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Washington. We also describe the current plans for our late-summer/early-fall exposed coal face tests at the WIDCO mine.

LABORATORY BLOCK TESTS

The laboratory block tests consisted of gasification of several coals using steam/oxygen injection and a drilled link between 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. Short-term goals include

- Development of an improved gas-analysis stream cleanup system for use during laboratory and field tests, with special emphasis on nonintegral water content measurements.
- Debugging of software used in data acquisition and reduction.
- A shakedown of the mobile gas-analysis-data-acquisition and control center installed in a trailer facility.

Long term goals include

- Obtaining data on the performance and cavity development as a function 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 using radiography.
- Obtaining results that will assist in the verification of gasification models.

EXPERIMENTAL APPARATUS AND PROCEDURES

The basic coal reactors consist of modified 55 gallon drums. Coal blocks roughly the size of the drums were collected at the various mines and shipped in water to the laboratory where they were potted into the drums using plaster of paris. For each run a new reactor was constructed.

Standard reactor preparation procedure after potting is as follows:

- Drill a 5/16-in. (0.79-cm) hole through the axis of coal and barrel with the bedding planes parallel to the ground.
- Drill a 1-in. (2.54-cm) hole about 8 in. (20 cm) into the barrel on the injection end.
- Emplace an igniter consisting of nichrome wire, wax, wood, and cotton at the end of the hole in the coal.
- Pot a 1/2-in. stainless steel tube into the remaining 1-in. hole to be used as the injection point.
- Drill and install 3 vertical traveling thermocouple wells. These are drilled with an approximate spacing of 6 in. (15 cm) down the length of the 24-in. (60-cm) borehole starting 6 in. (15 cm) from the end of the injection tube. Stainless steel tubes of 1/8- or 3/16-in. diameter are inserted to carry the thermocouples.
- Drill an exhaust hole about 3 in. (8 cm) into the end of the barrel and about 1 in. (2.5 cm) into the coal.
- Pot a 1-in. stainless steel tube into the hole to be used as an exhaust point.
- Fill the remainder of the barrel with plaster and place a 1/2-in. steel plate over the end.
- Place a 1-in. pipe around the stainless steel production tube and thread into the plate to serve as a gas seal.

Injected gas is supplied to the reactor through the 1/2-in. injection tube by a series of metered flows and a steam generator. The orfice meters allow known flows of argon, oxygen, air, and carbon dioxide to be used. Steam is generated by using a metering pump to introduce a known flow of water into the gas stream and then passing this stream inside a stainless steel tube through a heated and temperature-controlled copper block.

Part of the product gas from the reactor is cleaned before it is passed to the gas analysis

equipment. The gas to be cleaned first enters a dropout tank to catch large particles and allow mixing of metered amounts of cooling water. It then passes into a small cyclone separator designed to remove particulates. Next the gas is cooled in a set of two condensers to drop out the water and tars. Finally, the gas is passed through a series of two filters (25 and 5 μ), an orifice metering station, and then to a pump that moves the gas to the analytical equipment trailer. In addition, the system is provided with a bypass line so that only a portion of the product flow needs to be sent through the cleanup system.

The water content of the gas is measured in two ways. First an integral value for water (and tar) is provided by measuring the amount of condensate and determining the total dry gas flow. We attempted to obtain instantaneous measurements using a newly available hygrometer, which uses the impedence change of an RF signal coupled with a controlled Peltier chiller to determine dewpoint. This arrangement appears to be much less sensitive to upset and contamination than instruments based on chilled mirrors. However, problems with the construction of the head involving attachment of the temperature-sensing element to the chiller prevented the instrument from functioning to our satisfaction. Attempts are underway to overcome this problem. In the meantime we plan to evaluate the use of gas chromatography as a means of near-instantaneous measurement.

The dry gas is analyzed by three methods. The first and primary method for the short duration laboratory experiments is the use of a time-of-flight mass spectrometer. This instrument allows analysis to be done every 1 to 2 minutes. The second method is a set of three on-line gas meters, which analyze for specific components. We use two infrared meters to measure carbon dioxide and carbon monoxide. A fuel-cell based instrument is used for oxygen. Finally, a gas chromatograph is available although its usefulness as a real-time instrument was limited because of its relatively long (45 minute) turnaround time.

All thermal, pressure, flow, and gas composition data are automatically recorded during the experiment through the use of a minicomputer-based data acquisition system. The software currently in use is an upgraded version of that previously used during the Hoe Creek III field test. The software is now capable, we believe, of dealing with most geometries that might occur during a laboratory test or a full-scale field test. Much of the definition of the experimental configuration is embodied in a data base that can be readily changed from experiment to experiment. The computer system also provides for real time as well as post-experiment data reduction.

After a reactor is assembled and loaded into the system, a preburn check is run. This run consists primarily of flushing the system with carbon dioxide, checking for leaks and unusual pressure drops, checking flow meters, and ensuring that the gas is delivered to the analytical equipment. All heating elements are turned on and stablized.

A run generally lasts from 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 ignitor 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 runs to date, this has meant 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 are performed. During the latter stages of the burn it is often necessary to cool the product gas using water injection into the product line and also to bypass some of the flow around the gas cleanup system.

When the experiment is terminated a carbon dioxide purge is used to cool the reactor prior to examination. After cooling, the reactor is cut perpendicular to the axis at a point near the center (about 1 in. upstream of the center thermocouple). Photographs are taken and loose char and fused ash are removed for analysis. More photographs are taken and char is scraped from the sides of the cavity and saved for analysis. A final series of photographs is taken and samples of unaffected coal are used for analysis.

RESULTS

To date, a total of 7 runs have been performed on three different coals. Each of these experiments used a steam/oxygen ratio of 2/1 and a flow schedule that called for a quadratic (with time) increase in flow rate. The maximum flow of oxygen was 25 mmole/s and the time span of the experiments was set at 5 hours. This ensured that the burn would still be contained in the coal block, at least in the radial direction.

A brief summary of the runs is given in Table 1. Four of the tests were run for the scheduled 5 hours. Run WID-2 (WIDCO coal) was terminated early as a result of the burn extinguishing itself. Run HAN-1 (Hanna coal) developed a plug in the gas sample system as a result of a 1/2-in. piece of char being blown out of the production end, and was terminated early. Run WYD-1 (Wyodak coal) was shut down early as a result of a leak at the injection end of the reactor.

Table 1. Summary of the block experiments given in chronological order.

Run	Produced carbon (g atoms)	Average heat of combustion (kJ/mole)	Reason for termination
WID-1	406	215	Scheduled end
WID-2	63	137	Extinguished
WID-3	327	205	Scheduled end
HAN-1	118	225	Sample plug
WYD-1	89	182	Leak
WYD-2	311	191	Scheduled end
HAN-2	310	214	Scheduled end

Repeatability

While some evidence is available, not enough runs have been completed to make a clear statement of natural variability between runs using the same coal type and process parameters. Table 2 gives important process parameters for runs at the same coal consumption (carbon production). For three of the runs listed, only partial data are given.

For the two WIDCO runs, reasonably consistent results obtain although there is a 4% difference in the fraction of the consumed coal energy produced as combustible gas. Due to an upset in operation, the WYD-1 run is not a totally clean repeat. The variance in sensible heat fraction and average product temperature is more a function of a change made in measurement procedure than a true difference in runs. (Note that the WID-2 run had to be terminated because the gasification was extinguished.)

Table 3 gives compositions for the coals used in all runs. Some data are only preliminary, however the table indicates that a high ash content was probably the reason for the peculiarity of the WID-2 run. The table

Table 2. Average results of available duplicate runs at the same total carbon produced for each of the three coals studied.

	WIDCO		Hanna		Wyodak	
Measure	WID-1	WID-3	HAN-1	HAN-2	WYD-1	WYD-2
Carbon produced (g atoms)	328	328	118	118	89	89
Dry gas composition						
Ar	0.017	0.017	0.017	0.024	0.015	0.024
O_2	0.0005	0.003	0.0034	0.0007	0.006	0.015
H_2	0.357	0.367	0.355	0.321	0.328	0.287
CH_4	0.031	0.027	0.042	0.035	0.025	0.029
CO	0.238	0.238	0.247	0.217	0.200	0.146
CO_2	0.342	0.335	0.308	0.376	0.397	0.461
C_2H_4	0.008	0.006	0.011	0.009	0.006	0.008
H_2S	0.0077	0.0024	0.0015	0.0049	0.0013	0.0009
Product-gas heat of combustion (kJ/mole)	209	205	224	197	181	160
Reaction stoichiometry (O_2/C)	0.54	0.51	0.49	0.64	0.50	0.67
Energy distribution (fractions)						
Combustible gas	0.67	0.73	0.70	0.63	0.58	0.50
Gas Sensible heat	(0.05)[a]	0.15	0.09	0.16	0.08	0.19
Product heat of combustion per mole O_2 (kJ/mole)	623	644	710	486	576	367
Average product temperature (°C)	(325)[b]	566	458	650	528	702

[a]Fraction based on consumed coal energy estimated from produced carbon.
[b]Low value from poor thermocouple placement.

Table 3. Coal composition.

Measure	WIDCO			Hanna		Wyodak	
	WID-1	WID-2	WID-3	HAN-1	HAN-2	WYD-1	WYD-2
Weight fraction water	0.184	0.172	0.199	0.095	0.119	0.269	0.259
Weight fraction ash	0.090	0.272	0.14	0.069	0.029	0.023	0.032
Specific gravity	1.35	1.48	1.30	1.36	--[a]	--[a]	--[a]
Coal chemistry (dry basis)							
H/C	0.95	1.14	0.92	0.87	0.90	1.01	1.01
O/C[b]	0.17	0.19	0.19	0.16	--[a]	--[a]	--[a]
N/C	0.017	0.018	0.018	0.016	0.017	0.014	0.010
S/C	0.009	0.0032	0.0034	0.0022	0.0042	0.0030	0.0022

[a]Data not available at this writing.
[b]Oxygen by difference.

shows that WIDCO coal is a relatively inhomogeneous coal, thus rendering comparisons of operating strategies difficult.

Comparison runs for the Hanna and Wyodak coals show much greater variability than WID-1 and WID-3 runs. However, the period of comparison is only over initial stages of gasification, and we have found the greatest sensitivity of results during this initial low-flow period. We hope in the future to run full-term replications for these coals and expect the repeatability to be much better than shown in Table 2, particularly for relatively homogeneous Wyodak coal.

Also of interest with respect to the Hanna coals was the plugging problem encountered with the HAN-2 run. No internal channel plugging was noticed during the HAN-1 run but the initial attempts to ignite and gasify the HAN-2 block resulted in internal blockage of the borehole on 3 successive tries. Blockage occurred only minutes after ignition. The HAN-2 reactor was partially dismantled and a new 1/2-in. borehole was drilled to overcome the problem.

Comparison of Coal Performance

A smooth run was completed for each of the three coals examined, and results are summarized in Table 4. The Hanna run had the highest average dry-gas heat of combustion, but the WIDCO run yielded the highest coal energy recovery in the dry product gas, as well as the highest total product-gas heat of combustion per mole of oxygen injected. While this latter number is subject to errors in flow metering, the energy fraction number is not; therefore, it appears to represent a real difference. However, the coal heat of combustion used in the analysis is an estimated number and the energy fraction number may change somewhat when the actual coal heat of combustion results are available.

The low sensible heat and product-gas average temperature for the WIDCO and Wyodak runs are quite similar. Hanna coal, however, shows a relative increase in CO and decrease in CO_2. This may be a result of the drier nature of Hanna coal. This increase in dryness is not borne out by the measured water content of the product gas. However, these are integral water numbers and, as a result of cooling water addition and gas bypassing, are subject to considerable uncertainty. We hope to improve the accuracy with the use of gas chromotographic analysis.

The most striking result from the three runs is not their differences but their similarity. The average heating value, for example, varies by only 10%. The similarity is even more striking if only the latter high-flow period of the tests are compared. Table 5 shows this comparison, which includes the period in which oxygen flow was increased from 14 to 25 mmole/s and represents nearly 2/3 of the carbon production for the tests. The average heating value only varied from 204 kJ/mole for Wyodak coal to 219 kJ/mole for Hanna coal.

Representative samples of ash, char, and tar analyses obtained for the runs are shown in Tables 6-10. WIDCO coal showed the highest ash fractions, and analysis of ash in the coal and fused ash samples is given in Table 6. The results are reported for the main components and are given as weight percents assuming the oxide forms shown. The high iron in the WID-1 fused sample was probably the result of melting

Table 4. Average results of the experiments run to completion for each of the three coals studied.

Measure	WIDCO (WID-3)	Hanna (HAN-2)	Wyodak (WYD-2)
Carbon produced (g atoms)	328	310	311
Dry gas composition			
Ar	0.017	0.019	0.018
O_2	0.003	0.0002	0.004
H_2	0.367	0.349	0.343
CH_4	0.027	0.026	0.023
CO	0.238	0.280	0.230
CO_2	0.335	0.310	0.367
C_2H_4	0.006	0.006	0.005
H_2S	0.0024	0.0055	0.0011
H_2O/dry gas (mole ratio)	1.4	1.4	1.6
Product-gas heat of combustion (kJ/mole)	205	211	191
Reaction stoichiometry (O_2/C)	0.51	0.57	0.57
Energy distribution[a] (fractions)			
Combustible gas	0.73	0.69	0.62
Gas sensible heat	0.15[b]	0.23	0.27
Product heat of combustion			
per mole O_2 (kJ/mole)	644	603	533
Average product temperature (°C)	566[b]	878	921
Total dry gas produced (mole)	522	494	494
Total gas injected (mole)			
O_2	167	175	178
H_2O(g)	322	344	344
Ar	8.7	9.3	9.1

[a]Fraction based on consumed coal energy estimated from produced carbon.
[b]No stainless steel production tube was present.

Table 5. Average results for gasification during the high-flow period (14 to 25 mmole/s O_2) for the three coals.

	WIDCO (WID-3)	Hanna (HAN-2)	Wyodak (WYD-2)
Carbon produced (g atoms)	202	184	193
Dry gas composition			
Ar	0.016	0.016	0.016
O_2	0.0	0.0	0.0
H_2	0.371	0.364	0.367
CH_4	0.024	0.021	0.020
CO	0.260	0.317	0.269
CO_2	0.322	0.272	0.323
C_2H_4	0.005	0.005	0.004
H_2S	0.0024	0.0059	0.0012
Product-gas heat of combustion (kJ/mole)	208	219	204
Reaction stoichiometry (O_2/C)	0.50	0.52	0.52
Energy distribution[a]			
Combustible gas	0.74	0.73	0.67
Gas sensible heat	0.20[b]	0.27	0.30
Product heat of combustion			
per mole O_2 (kJ/mole)	661	687	631
Average product temperature (°C)	700[b]	1010	1025

[a]Fraction based on consumed coal energy estimated from produced carbon.
[b]No stainless steel production tube was present.

Table 6. Ash composition of coal and slagged ash samples for the WIDCO tests.

Measure	WID-1[a]		WID-2[b]		WID-3[c]	
	Coal	Fused sample	Coal	Fused sample	Coal	Fused sample
Major components as oxides (weight fraction of ash)						
SiO_2	0.29	0.13	0.45	0.50	0.53	0.62
AlO_3	0.21	0.18	0.29	0.27	0.23	0.27
TiO_2	0.022	0.032	0.092	0.13	0.016	0.012
Fe_2O_3	0.097	0.21	0.019	0.025	0.040	0.043
CaO	0.16	0.48	0.061	0.085	0.093	0.10
MgO	0.016	0.024	0.011	0.007	0.017	0.015
SO_3	0.17	0.030	0.21	0.00003	0.038	0.0006
Fusion temperatures (°C) in reducing atmosphere						
Initial deformation	1191	--	1348	--	1271	--
Softening (H=W)	1210	--	1371	--	1288	--
Softening (H=1/2W)	1221	--	1466	--	1293	--
Fluid	1268	--	1479	--	1366	--

[a]Weight fraction of ash (wet basis) = 0.09.
[b]Weight fraction of ash (wet basis) = 0.272.
[c]Weight fraction of ash (wet basis) = 0.14.

Table 7. Char composition for WIDCO loose char samples removed from the gasification cavities.

Measure	WID-1		WID-3	
	Injection end	Production end	Injection end	Production end
Weight fraction ash	0.17	0.07	0.34	0.40
Atomic ratios				
H/C	0.40	0.25	0.17	0.24
O/C[a]	0.09	0.06	0.04	0.06
S/C	0.008	0.0057	0.0022	0.0053
N/C	0.015	0.010	0.0097	0.016

[a]Oxygen by difference.

Table 8. Char composition for WIDCO scraped char samples removed from the gasification cavities.

Measure	WID-1		WID-2		WID-3	
	Injection end	Production end	Injection end	Production end	Injection end	Production end
Weight fraction ash	0.112	0.089	0.52	0.62	0.26	0.28
Atomic ratios						
H/C	0.33	0.43	0.47	0.59	0.26	0.41
O/C[a]	0.07	0.09	0.12	0.15	0.07	0.09
S/C	0.0071	0.0072	0.0033	0.0050	0.0026	0.0024
N/C	0.013	0.012	0.012	0.0014	0.014	0.017

[a]Oxygen by difference.

Table 9. Char composition for Hanna and Wyodak scraped char samples removed from the gasification cavities.

Measure	HAN-1		HAN-2		WID-2	
	Injection end	Production end	Injection end	Production end	Injection end	Production end
Weight fraction ash	0.05	0.04	0.08	0.07	0.066	0.064
Atomic ratios						
H/C	0.29	0.36	0.16	0.21	0.36	0.34
O/C[a]	0.09	0.07	0.04	0.04	0.076	0.083
S/C	0.0025	0.0023	0.0077	0.0067	0.002	0.0022
N/C	0.014	0.018	0.0067	0.0010	0.010	0.010

[a]Oxygen by difference.

Table 10. Tar quantity and composition for the collected samples.

Measure	WIDCO		HANNA		WYODAK	
	WID-1	WID-3	HAN-1	HAN-2	WYD-1	WYD-2
Kg tar per kg produced H_2O	0.0096	0.012	0.015	0.012	trace	0.0059
C in tar per C in product gas	0.008	0.026	0.042	0.037	--[a]	0.014
Atomic ratios						
H/C	1.66	1.67	1.31	2.00	--[a]	1.49
O/C[b]	0.40	0.34	0.22	0.63	--[a]	0.37
S/C	0.0098	0.0033	0.0022	--[a]	--[a]	--[a]
N/C	0.0087	0.0074	0.012	0.011	--[a]	0.004

[a]Data not available at this writing.
[b]Oxygen by difference.

a thermal well. The relatively high fluid temperatures for the WID-2 ash may have been another reason for the difficulty in burning WID-2.

The char analyses in Tables 7-9 show the variations of composition one would expect with respect to sampling point. Those taken from the injection end show lower hydrogen contents. The ash content is less consistent, partly as a result of removing ash samples from the system. The WID-3 loose char samples (see Table 7) appear to have undergone more pyrolysis than those scraped from the walls (see Table 8). In these analyses, one should bear in mind the difficulties in sampling. Loose char, for example, may not have been loose during the burn but knocked loose in cutting open the block. In addition, the scraping of char from cavity walls is, by its very nature, somewhat arbitrary.

Table 10 represents analysis of the small amount of tar collected. Collection of tar is difficult, and the tar amounts indicated are only semiquantitative. The amount of tar collected is nearly an order of magnitude less than would be produced by pyrolyzing the consumed coal. This is not a surprising result in light of the geometry of the system.

Product-gas heat of combustion and major-component-dry-gas composition as a function of total carbon produced are shown in Figs. 1-9 for runs in each of the three coals. After the initial startup period (0 to 100 gram atoms of carbon) the heating values are relatively constant. The response to the flow-rate changes were much more marked early at the low flows than later at the higher flows. In all cases the tendency is for an initial increase followed by a relatively rapid decay. The larger responses at the low flow are probably a result of the more dominant role of heat losses at these low rates. The total energy input is more or less proportional to the oxygen flow rate while many of the heat loss mechanisms do not necessarily increase in proportion to the flow, and thus represent a smaller fractional loss. Once a certain level of

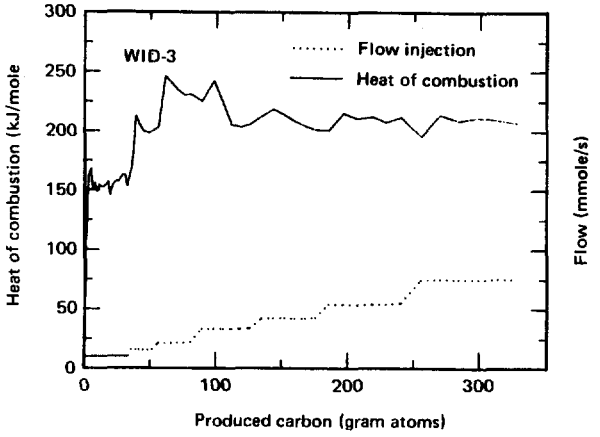

FIG. 1. Dry product-gas heat of combustion for the WID-3 experiment.

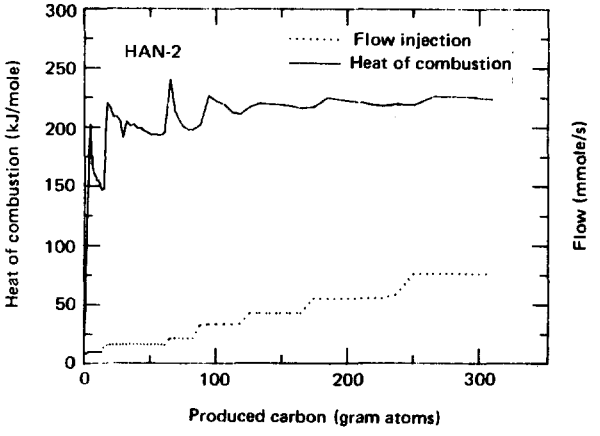

FIG. 2. Dry product-gas heat of combustion for the HAN-2 experiment.

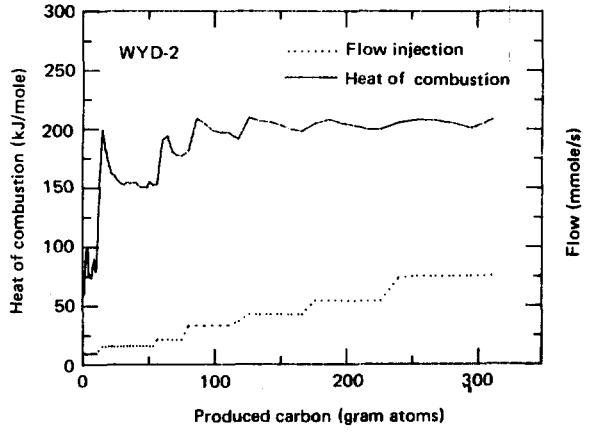

FIG. 3. Dry product-gas heat of combustion for the WYD-2 experiment.

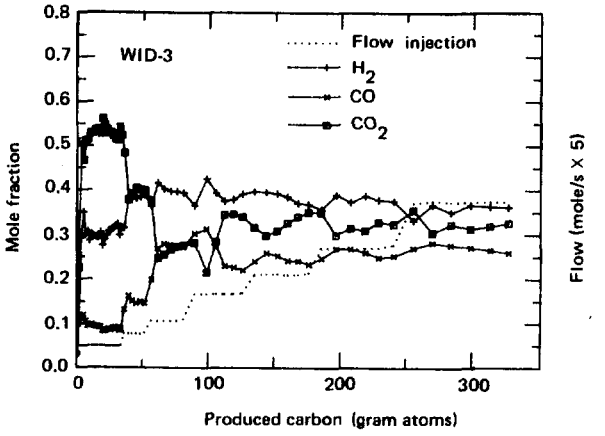

FIG. 4. Hydrogen, carbon monoxide, and carbon dioxide mole fractions in the dry product gas from the WID-3 experiment.

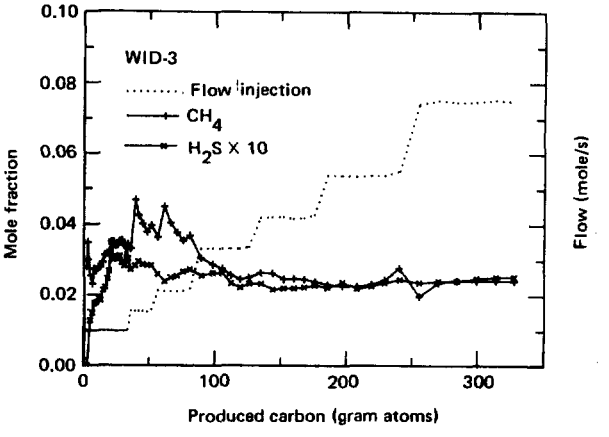

FIG. 5. Methane and hydrogen sulfide mole fractions in the dry product gas from the WID-3 experiment.

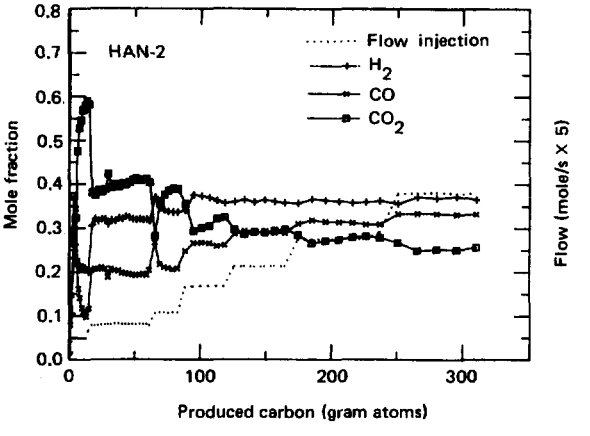

FIG. 6. Hydrogen, carbon monoxide, and carbon dioxide mole fractions in the dry product gas from the HAN-2 experiment.

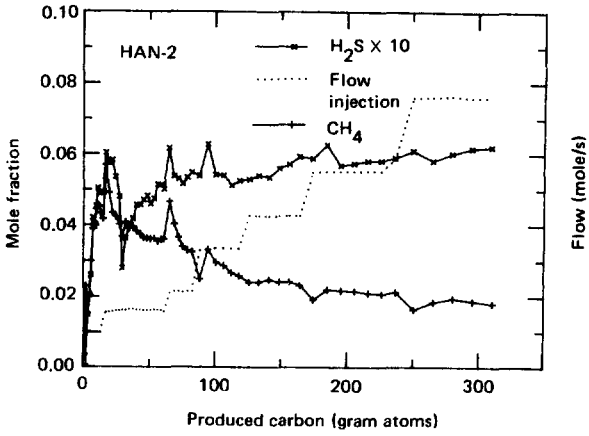

FIG. 7. Methane and hydrogen sulfide mole fractions in the dry product gas from the HAN-2 experiment.

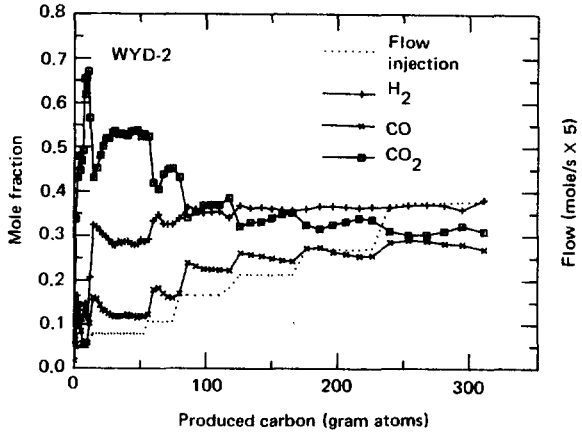

FIG. 8. Hydrogen, carbon monoxide, and carbon dioxide mole fractions in the dry product gas from the WYD-2 experiment.

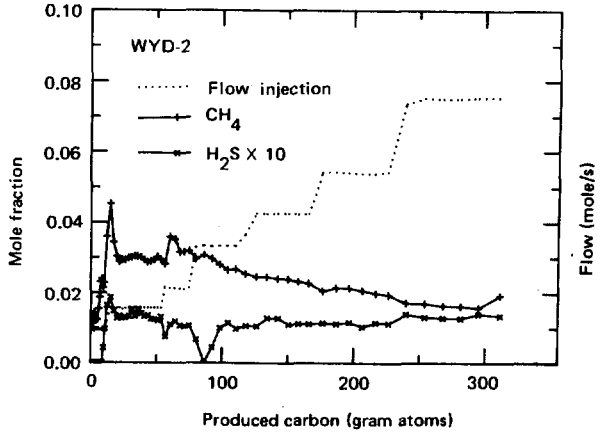

FIG. 9. Methane and hydrogen sulfide mole fractions in the dry product gas from the WYD-2 experiment.

flow is reached, however, one observes a decoupling between heating value and flow rate.

Several points can be made about the course of the gasification experiments by examining the dry gas composition plots in Figs. 4-9. First, the early flow changes had a marked and lasting effect on CO and CO_2 concentration. The CO increased rather dramatically, and CO_2 decreased as the flow increased. This, again, is probably a result of the change in importance of heat loss terms. The H_2 concentration also responded to these early changes, but at a reduced level. Noteworthy in all runs is the relative consistency of the H_2 levels after the initial startup period. During the later period of tests (after about 100 gram atoms), when the O_2 flow had reached about 11 mmole/s, the changes of CO and CO_2 for WIDCO and Wyodak coals tended to decay after a flow change, while those for Hanna coal seemed to persist.

In all cases the level of methane tended to decline with coal consumption while H_2S remained relatively constant (see Figs. 5, 7, and 9). For methane, this is probably a result of the decrease in pyrolysis along with a possible increase of combustion of pyrolysis products with time. On the other hand, the constant H_2S levels indicate that sulfur removed from the coal is uniformly transformed to H_2S during the entire process.

Figures 10-12 show the temperatures measured along the gasification channel by the traveling thermocouples and the exhaust thermocouple. The plots show temperature of the traveling thermocouples at a position as near the original borehole as possible. The distance shown for the traveling thermocouples

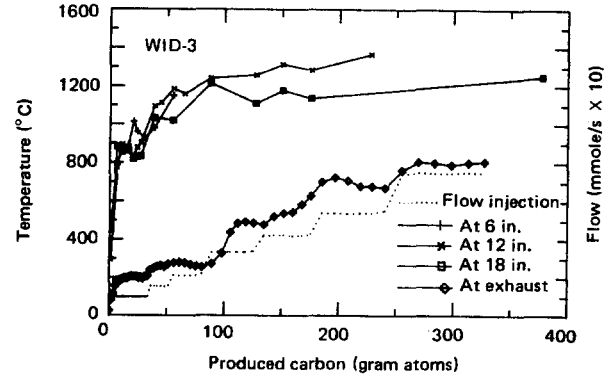

FIG. 10. Temperatures along the axis of the borehole and at the exhaust point for the WID-3 experiment. Positions are approximate distances from the end of the injection tube. (1 inch = 2.54 cm.)

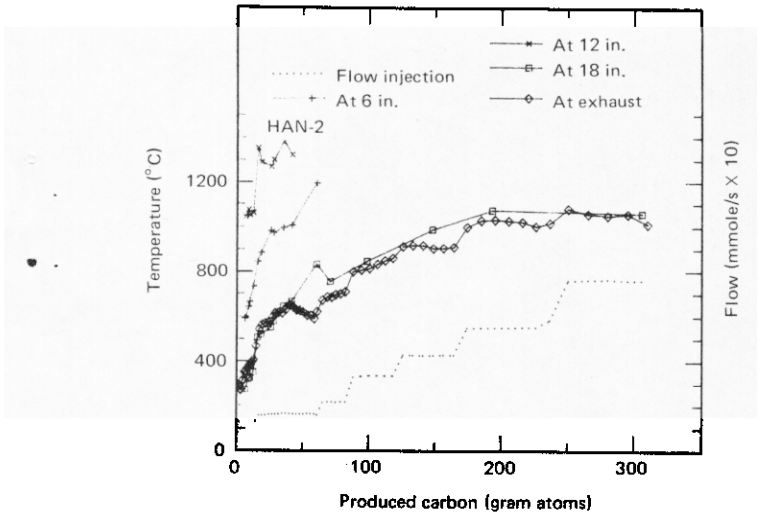

FIG. 11. Temperature along the axis of the borehole and at the exhaust point for the HAN-2 experiment. Positions are approximate distances from the end of the injection tube. (1 inch = 2.54 cm.)

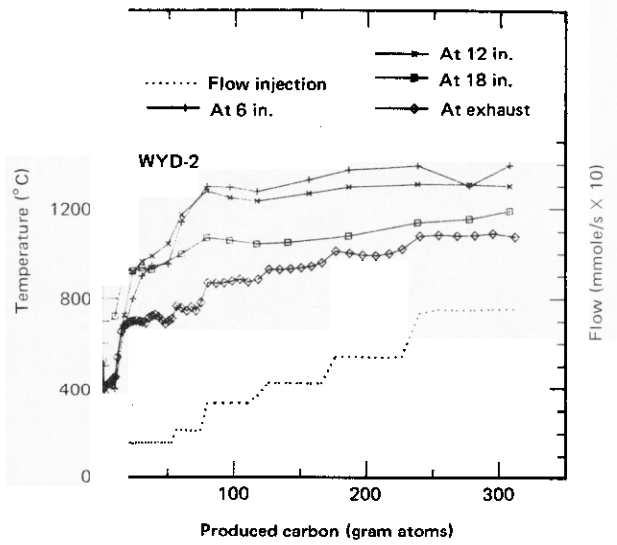

Fig. 12. Temperatures along the axis of the borehole and at the exhaust point for the WYD-2 experiment. Positions are approximate distances from the end of the injection tube. (1 inch = 2.54 cm.)

is approximate and is measured from the end of the injection tube. The traveling thermocouple values are influenced by the drilled hole during the early burn phases and, as a result, may not indicate maximum temperatures. Later (after 100 gram atoms of carbon) they represent the maximum temperature at that axial position. In many cases the temperature responses stop before the burn as a result of destruction of the thermocouple. The low value of the exhaust temperature for WID-3 is a result of the lack of a 1-in. stainless exhaust tube, as mentioned previously. In general the plots indicate similar temperatures of approxiately 1000 to 1300°C during most of the runs. The temperature drop down the axis is apparently not large, with WYD-2 indicating approximately a 200°C difference between the 6- and 18-in. positions.

Figures 13-21 are photographs of the cut-open blocks. Included is a picture of both the injection and production halves for the WID-3, HAN-2, and WYD-2 runs. These pictures were obviously taken at the end of these experiments. They involved the production of about 300 gram atoms of carbon. Also included for the Hanna and Wyodak coals is a picture obtained from HAN-1 and WYD-1 runs at a much smaller coal consumption.

While no WIDCO coal intermediate run is available, Fig. 15 shows the WID-2 injection end. The figure is included to show that the strong fused-ash tube that developed around the initial borehole in this run was almost surely the cause of extinction of the WID-2 burn. One factor qualifying this conclusion is the fact that during this run we experienced difficulty with the steam generator, and it is possible that some wet steam was introduced. However,

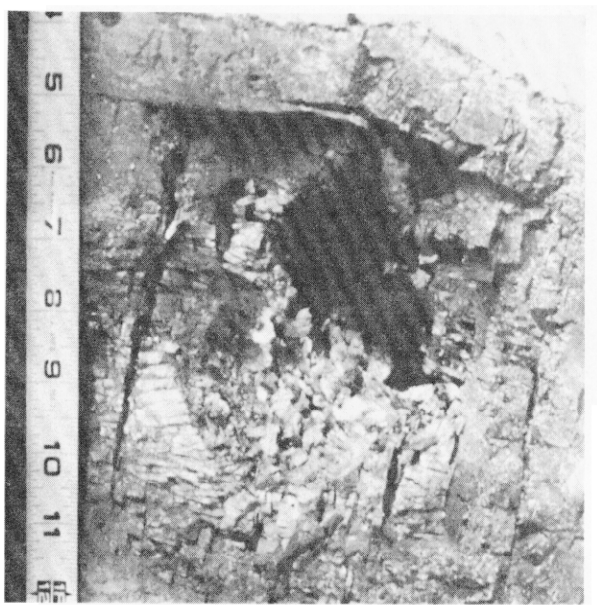

FIG. 13. Photograph of the injection half of the coal block at the end of the WID-3 experiment. (1 inch = 2.54 cm.)

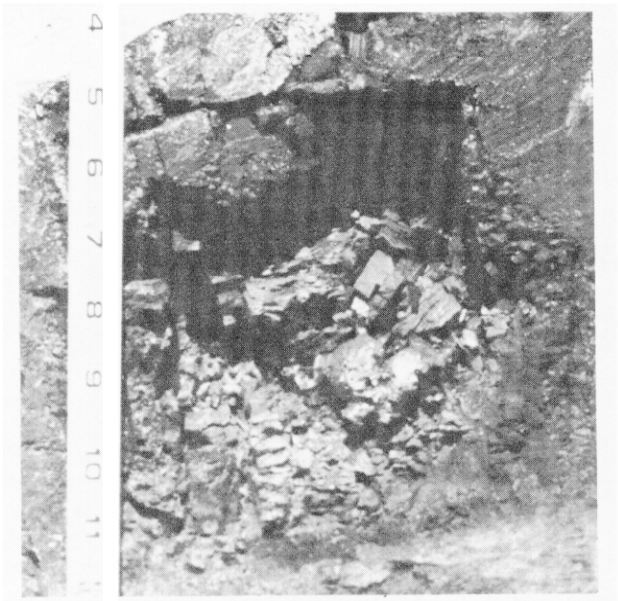

FIG. 14. Photograph of the production half of the coal block at the end of the WID-3 experiment. (1 inch = 2.54 cm.)

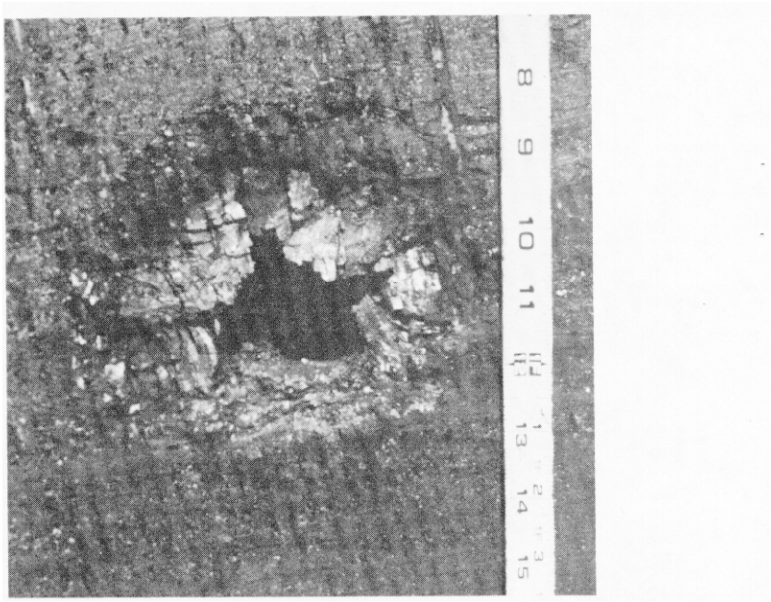

FIG. 16. Photograph of the injection half of the coal block at the end of the HAN-2 experiment. (1 inch = 2.54 cm.)

FIG. 15. Photograph of the production half of the coal block at the end of the WID-2 experiment. (1 inch = 2.54 cm.)

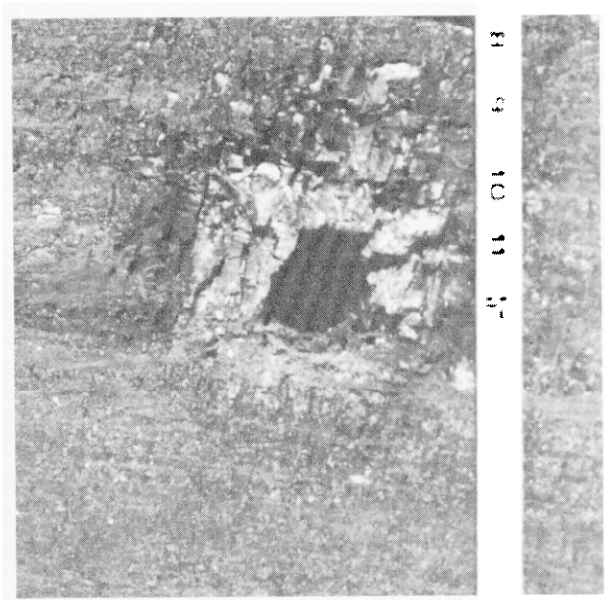

FIG. 17. Photograph of the production half of the coal block at the end of the HAN-2 experiment. (1 inch = 2.54 cm.)

FIG. 18. Photograph of the production half of the coal block at the end of the HAN-1 experiment. (1 inch = 2.54 cm.)

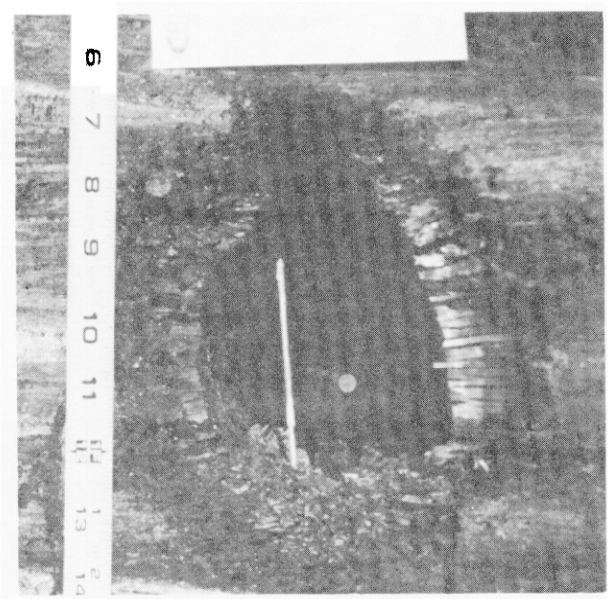

FIG. 19. Photograph of the injection half of the coal block at the end of the WYD-2 experiment. (1 inch = 2.54 cm.)

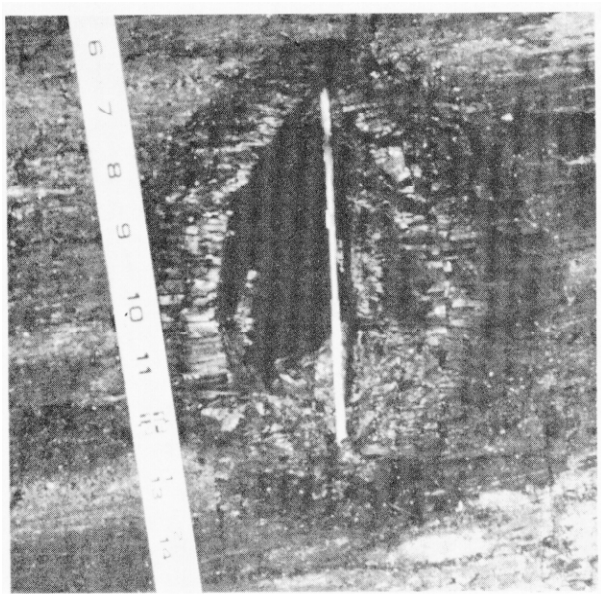

FIG. 20. Photograph of the production half of the coal block at the end of the WYD-2 experiment. (1 inch = 2.54 cm.)

FIG. 21. Photograph of the production half of the coal block at the end of the WYD-1 experiment. (1 inch = 2.54 cm.)

when it appeared that the WID-2 burn was going out we shifted to pure oxygen injection for a period of 10 minutes, but this seemed to have no effect.

The appearance of the burn cavity in each of the three coals was markedly different. Conclusions drawn from photographs and visual inspection are summarized in Fig. 22. The WIDCO cavity had a circular coal-affected zone and an approximately concentric ring of char adhering to the walls. Inside this char ring was a considerable amount of rubble consisting of char and fused ash. This rubble accumulation distinguished it from the other coals. The Hanna coal cavity was open, but was much smaller than that in the other coals. The affected zone was circular and the concentric char ring was relatively thicker and stronger than for other coals. Wyodak coal exhibited an asymmetric cavity elongated in a direction perpendicular to the bedding plane. Our previous work[2] had shown that this elongation is not influenced by gravity or cleat direction, but is only a function of the bedding plane orientation. The char ring showed a definite thinning near the top of the cavity. The void region was essentially rubble free.

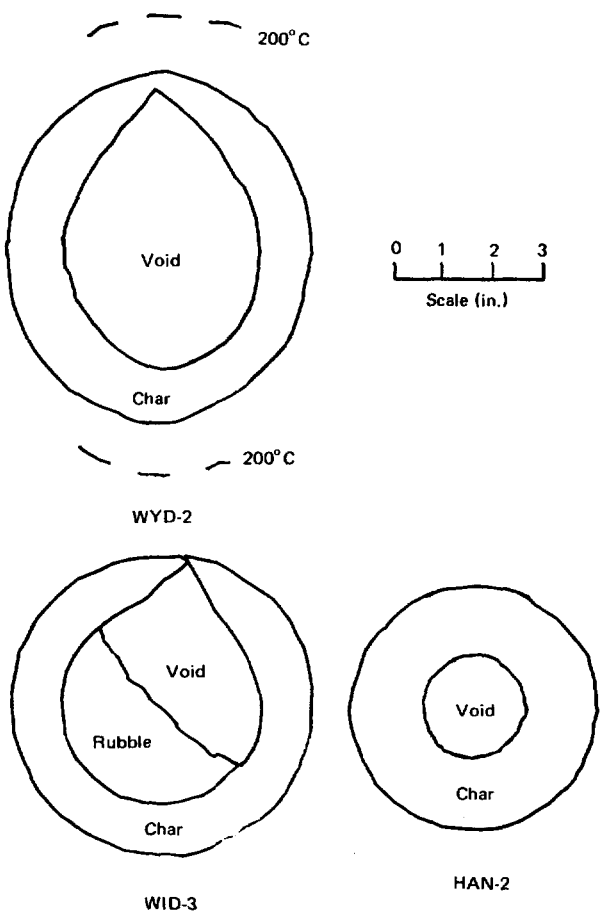

FIG. 22. Line drawings of the general cross sections observed at the end of the experiments in the three different coals. (1 inch = 2.54 cm.)

Also included in Fig. 22 is the rough location of the 200°C isotherm at the end of the WYD-2 experiment. The coal had obviously dried before reaching this temperature but no easily identified drying front could be observed by visual inspection.

Traveling thermocouples were used to track the expanding hot zone and peak reactor temperatures. More often than not, however, they failed before completion of the test. Exceptions were those used in the WYD-2 run where all thermocouples lasted until shutdown.

Figure 23 shows the results of traverses of the thermocouple during the WYD-2 run. The general features are typical of those obtained for all the coals. The last traverse was completed just before shutdown and allows us to draw the void boundary at this time on the figure. There is some uncertainty with respect to absolute location of the void boundaries but the distance between the upper and lower boundary is accurate to within about 1 in. It is interesting to note that the boundary location suggests that the hottest temperatures at this axial position exist in the gas phase. This is consistent with the presence of gas phase oxidation at this particular axial position or with the notion that combustion was completed upstream, yielding a hot gas that flows downstream to gasify, pyrolyze, and dry the coal.

Survival of the WYD-2 thermocouples allows us to picture the radial growth of the gasification region along the axis of the burn. Figure 24 shows the 400°C isotherm (at two times) inferred from the traveling thermocouple readings and the final cavity shape. This general shape is typical of all the coals studied. Location of the injection and production position are approximate, but the thermal traces confirm a greater upward than downward growth from the original borehole. Upward growth was also observed in WIDCO coal, but the Hanna cavity grew, if anything, more downward than upward. Downward growth is believed to be due to a shaly parting some inches above the original, drilled hole. In the future we hope to obtain more information about changes in cavity shape with coal consumption by taking radiographic pictures of the reactor during a run.

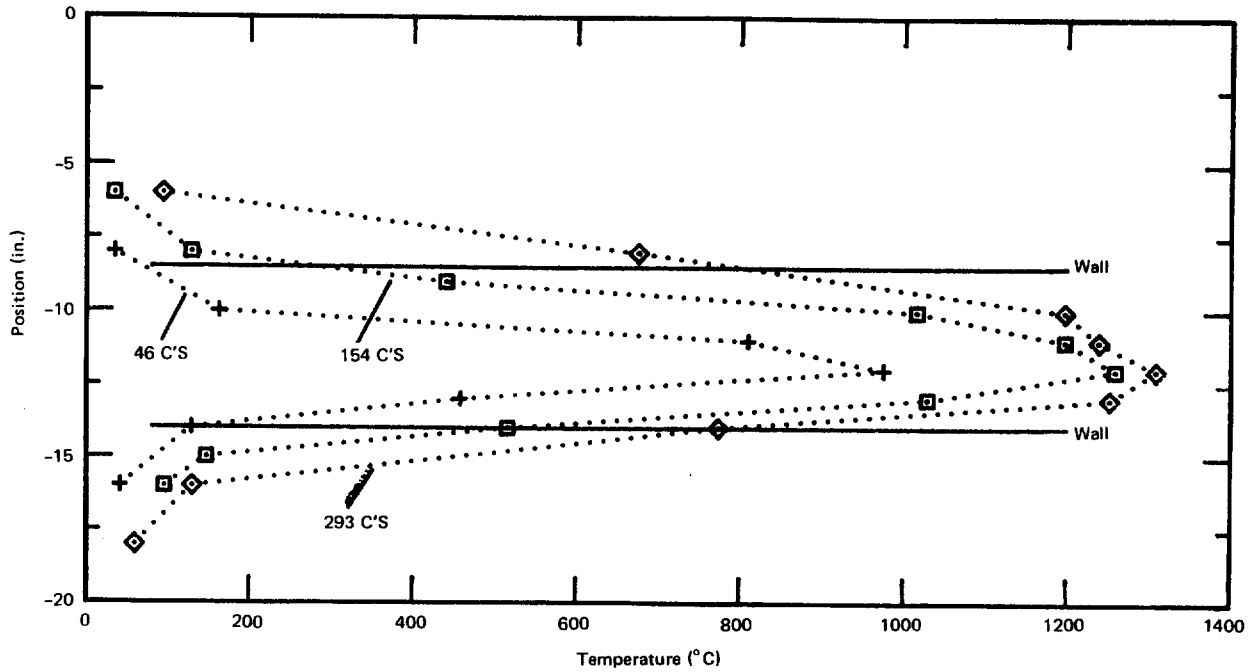

FIG. 23. Temperature profiles from the center traveling thermocouple at three times during the WID-2 experiment. Also shown is the approximate location of the walls at the end of the experiment. (1 inch = 2.54 cm.)

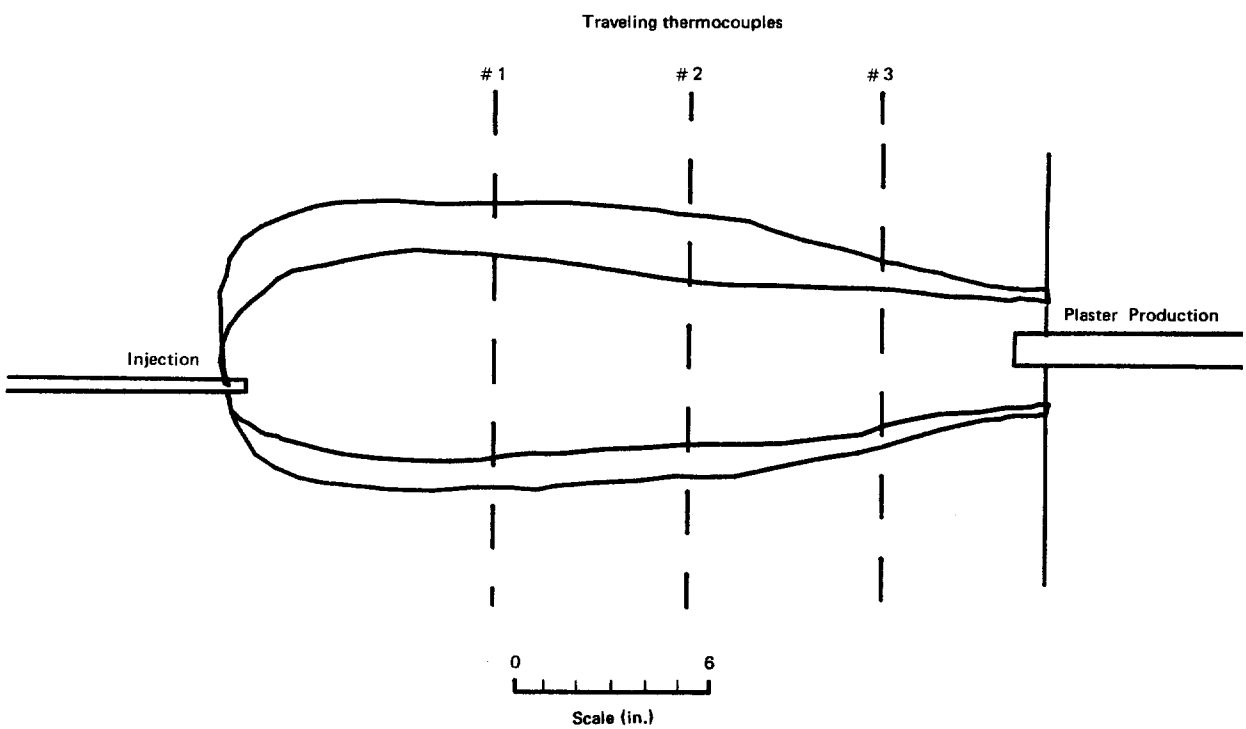

FIG. 24. The approximate cavity profile at two times during the WYD-2 experiment as inferred from the location of the 400°C isotherm. (1 inch = 2.54 cm.)

CONCLUSIONS

The experiments to date lead to two tentative conclusions. First, on a small laboratory scale, the three coals studied yield different cavity shapes. Second, the differences in cavity shape have little apparent influence on product-gas heating value.

FUTURE PLANS

We hope to continue our laboratory-scale block experiments. Currently our plans are focused on the following items.

- The repeatability of results.
- The use of pure carbon to look at energy transport versus mass transport.
- The influence of different steam/oxygen ratios.
- The influence of different flow schedules.
- The use of radiography to determine the time history of cavity development.
- The possible use of longer blocks of coals.

LARGE BLOCK TEST

Objective

The basic objective of the large-block experiments is to quantify the early cavity growth at a scale large enough to allow safe extrapolation to field situations.

As part of a cooperative program involving the Laramie Energy Technology Center (LETC), Sandia Laboratories, WIDCO, and the State of Washington, we are planning six gasification experiments in drilled channels at an exposed coal face on the WIDCO property near Centralia, Washington. The specific goals for these experiments are:

- To determine the burn cavity shape and degree of rubble fill for a coal consumption of approximately 27 m^3.
- To determine the composition and particulate production as a function of operating conditions through the burn.
- To observe linking channel growth due to hot gas flow.
- To observe the extent of slag formation from parting zones and coal ash and determine any interactions with the burn process.
- To determine any significant differences in cavity growth or process behavior due to changes in oxygen/steam ratio.
- To compare the results for oxygen/steam gasification with an air burn.
- To observe the effect of roof interaction and to do a small-scale test of the controlled retracting injection point (CRIP) concept.
- To compare results with smaller-scale laboratory block tests.

Description of the Experiment

Schematic views of the experimental arrangement are shown in Figs. 25-27.

A "drain hole" type drilling rig will be used to drill a hole parallel to the coal seam floor. A vertical hole will be drilled from above to intersect with the end of the slant hole. The vertical hole will be cased and used as the production well. The initial part of the slant hole will be cased and used as the injection well. Ignition of the coal will take place at the end of the oxygen lance. Oxygen/steam or air will be supplied at slightly over 1 atm to minimize gas leaks. Preburn pressure and flow test will be used to find and seal any detectable leak paths at the coal face.

After ignition the coal will be gasified until approximately 27 m^3 of coal have been consumed. When the cavity has reached the desired size, the burn will be extinguished by turning off oxygen and flowing steam and, if necessary, water will be injected until the cavity has cooled to a safe level for inspection.

An inspection well, drilled before the burn, will be used for visual cavity inspection. This well will be drilled to intersect the planned cavity and will be used with a remote controlled TV system to observe and measure the cavity size. The inspection well will be equipped with a shutoff valve and an optical window for possible visual inspection and optical pyrometry during the later part of the burn.

After the burns are completed, the burn cavities will be filled with cement grout and then excavated for further inspection and sampling.

Visual inspection and measurement of the burn cavities are expected to provide the most

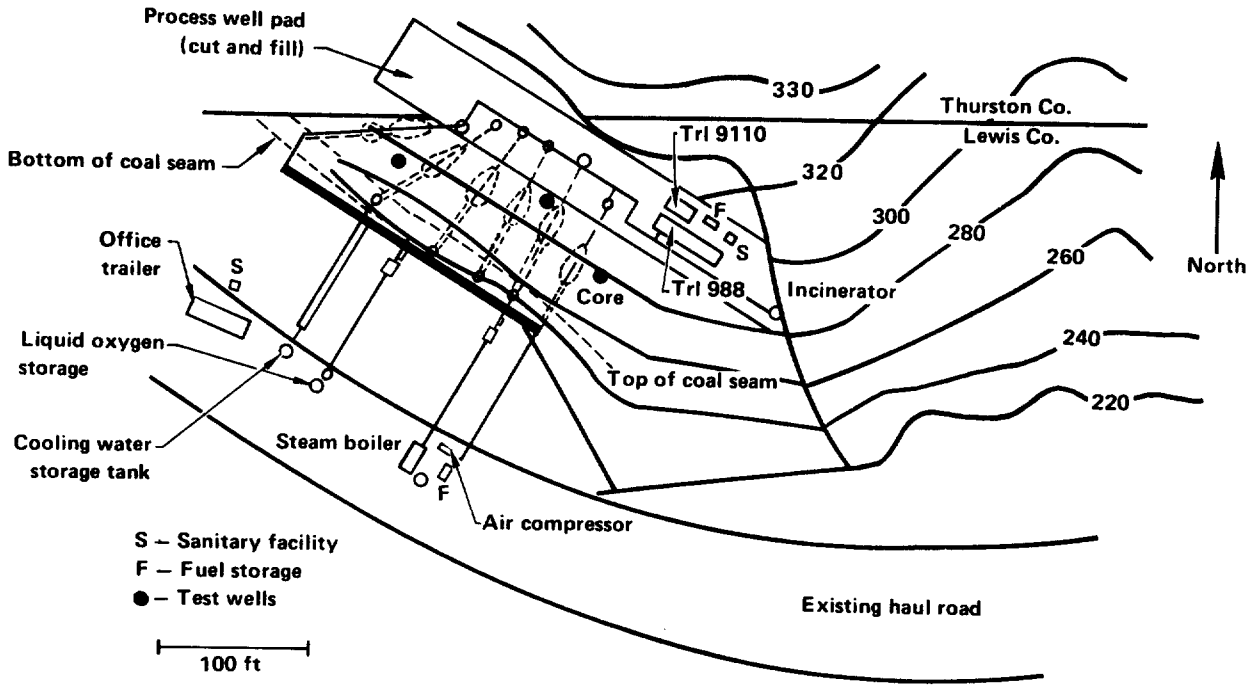

FIG. 25. Plan view of the large block experiment. (1 ft = 0.3 m.)

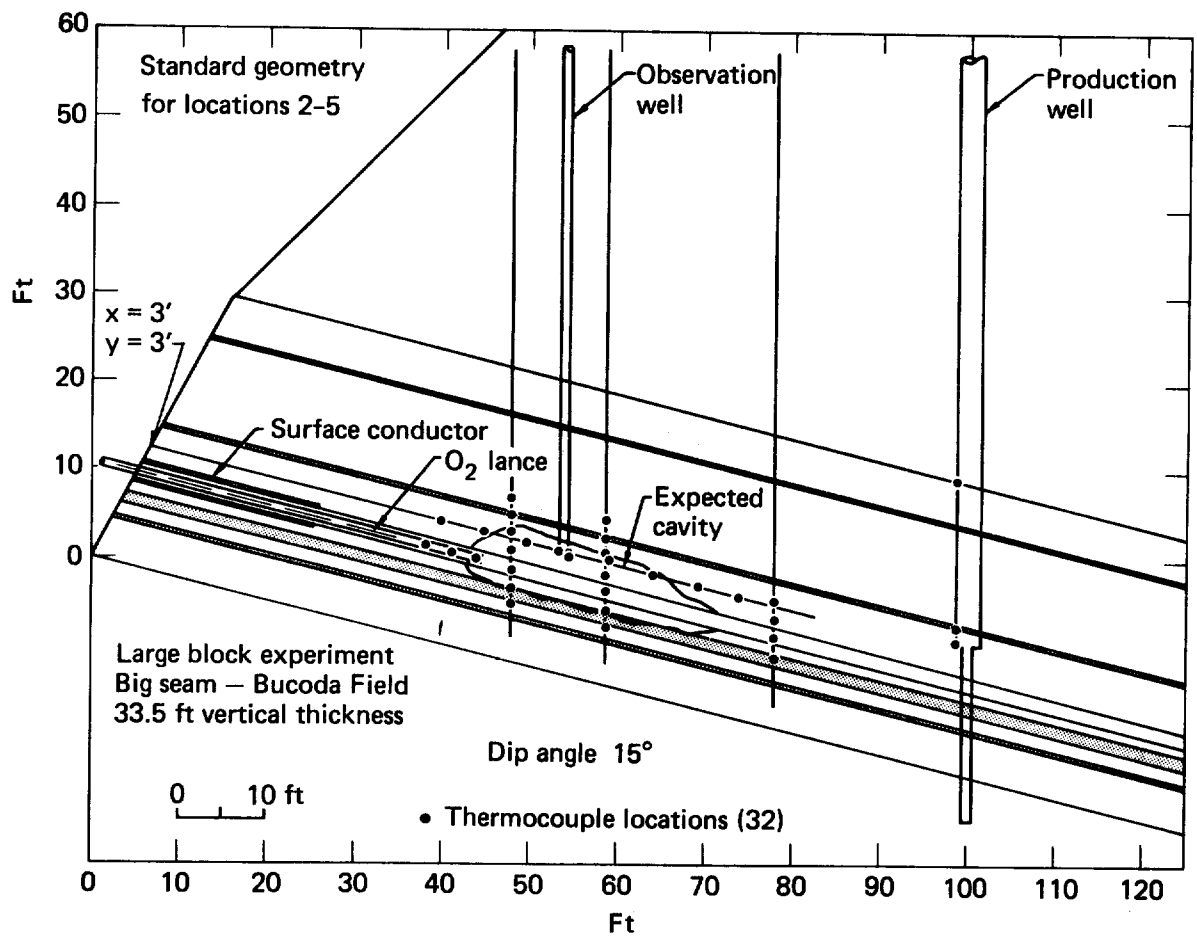

FIG. 26. A typical cross section for experiments 2-5. (1 ft = 0.3 m.)

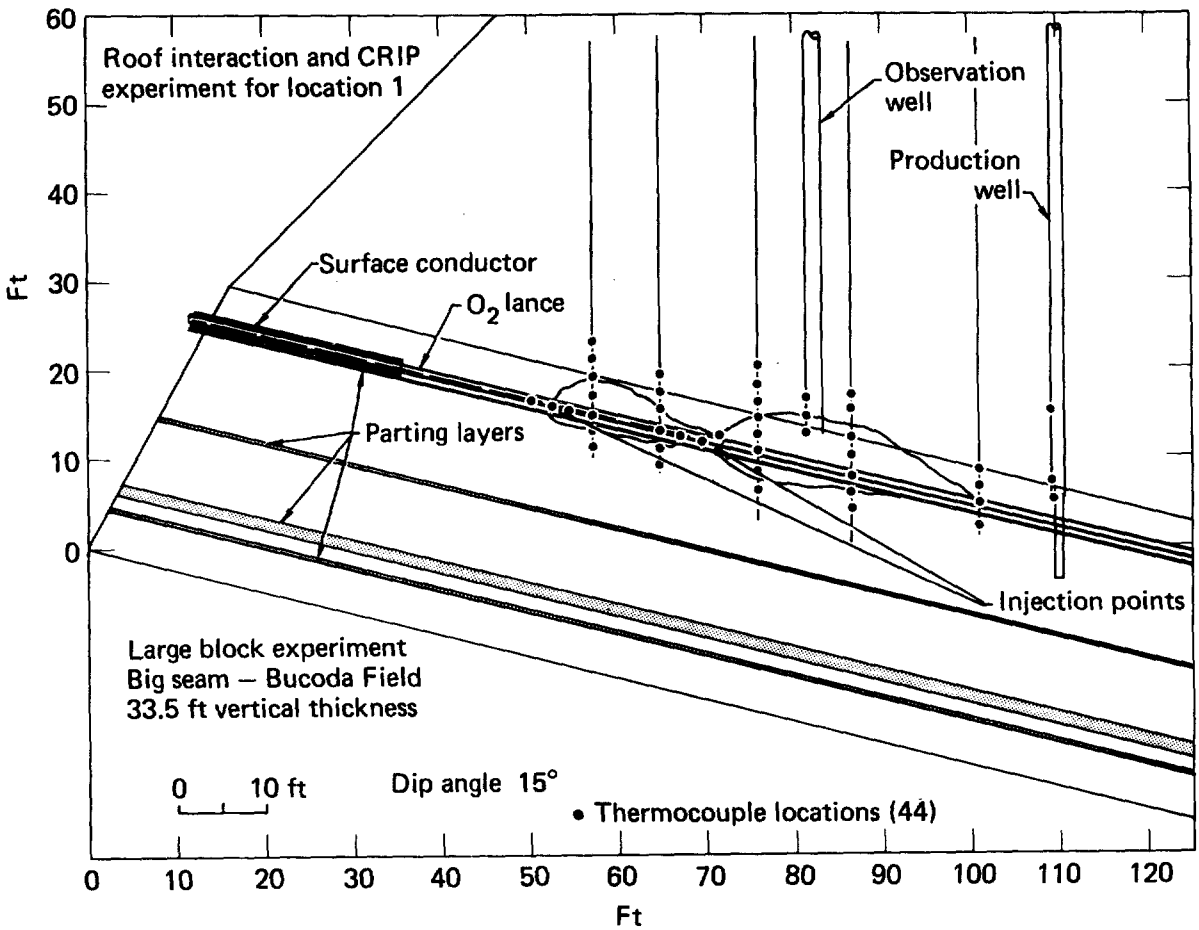

FIG. 27. The cross section for the roof interaction and CRIP experiment. (1 ft = 0.3 m.)

important diagnostic information from these experiments. Size and shape of the cavity, condition of the walls, degree and type of rubble or slag filling, and state of the gas-flow channel are all factors that can influence our ideas on the way the process operates.

Real-time instrumentation will be used to diagnose the burn progress. A few thermocouple strings will be emplaced horizontally and vertically. These will serve to keep track of the gross features of the burn zone as a function of time. The proposed thermocouple locations are shown in Figs. 26 and 27. Standard gas flow, pressure, and gas chemistry measurements will be made using the LLNL data acquisition facility.

One of the burns will provide a calibration test for the high-frequency electromagnetic wave mapping (HFEM) detection system[4] and also test a newly developed ultrasonic thermometer system.[5]

Test Plan

Four steam/oxygen experiments are planned. Three will be done in the main part of the coal seam with stratigraphy as uniform as possible, and one will be located near the top of the coal seam so that the cavity will reach the roof and begin to interact. The first three experiments will test the effect of flow rate and steam/oxygen ratio on cavity growth.

Two additional experiments will be included. The first, combined with the roof interaction test, will test the CRIP system.[6] The basic concept in this experiment is that after the roof has collapsed into the burn zone and gas quality has deteriorated, a section of injection pipe is deliberately destroyed to allow the burn to move back and reestablish itself in fresh coal, thus creating a new cavity upstream from the old one. The new burn will be stopped before it has interacted with the roof so that,

upon excavation, both stages of cavity formation can be seen.

The second test will be an air-injection test designed to compare cavity growth and gas composition for air and oxygen/steam burns. The air flow rate will be chosen to give the same oxygen content as one of the previous oxygen/steam tests. A supplementary goal of the TONO-1 test plan includes a period of air burn. This test will aid in evaluating proper operating parameters to meet that goal.

The series will be started by igniting a very lightly instrumented practice burn in the sixth hole location. This will be an air burn that will run long enough to check our operating system. The hole will be drilled below the large parting layer to compare cavity growth with the air burn to be done in a hole above that parting layer.

Operating Strategy

As described, four oxygen/steam injection experiments are planned. Three of the experiments are designed to test flow rate and oxygen/steam ratio dependence and the fourth is intended to test roof interaction.

We will vary the injection-flow rate so that it is proportional to the square of the operating time. This will maintain a constant oxygen flux per unit area of cavity and also a constant gas velocity.

The choice of a squared dependence for flow rate is somewhat arbitrary but was developed from 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 this test is a mid-scale test between the very small laboratory tests and the large-scale field test, and it is useful to have a means of tying all the tests together. Our hope is to be able to do this with the modeling effort, but currently we do not believe 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 have considered Reynolds number, Froude number, constant velocity, constant oxygen flux, constant residence time, and others. We then further assume that some single value of the chosen parameter is optimal 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, t the time, k a constant, and n varies according to the parameter chosen. (The exception to this power dependence for the parameters looked at is the constant residence time assumption, which leads to an exponential dependence on time.)

The attractiveness of this simple relation for flow is that it allows one to prescribe a nonarbitrary flow-rate schedule for a single experiment. It focuses on changing a single parameter, k, from experiment to experiment, and gives a method of scaling experiments. Our choice of n=2 was a result of our feeling that, of the simple parameters explored, the constant oxygen flux seemed to have the most merit and the resulting scaling between small and large experiments seemed to fit naturally within the framework of our operating experience. Of course, as we gain more experimental and modeling evidence we may modify the simple $f=kt^2$ schedule.

Each experiment will continue until $27\,m^3$ (40 tons) of coal have been consumed. These cavities should be large enough to illustrate most of the conditions encountered in the first few days of underground tests. The first two experiments will be done with the same oxygen/steam ratio but with different maximum flow rates. The third experiment will duplicate one of the flow rate schedules with a different oxygen/steam ratio. The fourth, or roof interaction experiment, will use the same oxygen/steam ratio and flow rate schedule as one of the first three tests. The pertinent flow rate and operating times are:

- Time for fast flow = 2.9 days
- Max. oxygen flow = 5.05 mole/s
- Time for slow flow = 5.8 days
- Max. oxygen flow = 2.53 mole/s
- Coal consumed = $27\,m^3$ (40 tons)
- Steam/oxygen ratios = 2/1 and 4/1.

High particulate emission or oxygen breakthrough at the production well may make it necessary to change the planned flow rate schedule. The purpose of these tests is to learn about burn cavity formation so the results of one test may very well modify our plans for the next tests.

The maximum flow rate for the air burn will be 12.7 mole/s, which will be equivalent to the slow-flow oxygen burn.

Site Geology and Hydrology

The site plan giving the experimental layout is shown in Fig. 25. The permitted area is defined by the county line and the natural outcrop of the seam. All six sites are contained within these boundaries.

Three test wells have been drilled, logged, and hydrologically tested, and one complete core was taken. The resulting stratigraphy is shown in Fig. 28 along with the corresponding natural gamma log.

Hydrologic testing indicates higher permeabilities in the top half of the coal seam and closer to the natural outcrop. The permeability of the bottom half of the coal seam appears to be in the several hundred millidarcy range, which should be adequate for controlling gas losses. Air-flow tests will be done before the start of gasification to determine loss rates.

Hardware

The processing systems designed to support the series of experiments will consist of conventional processing components assembled on portable or temporary structures for easy installation assembly. These components will provide for supplying injection gases to the process, controlling critical parameters of the process, and disposing of exhaust gases generated within the gasification reaction zone. Auxiliary systems will include a product-gas conditioning (cleanup) system to accommodate an on-site gas analysis installation and a cooling/quench water system used to control high-temperature zones where it is desirable to avoid thermal damage to components.

Injection Gas Systems. Steam and oxygen will be supplied to the experiment from trailer-mounted and/or mobile units. Steam will be provided by a trailer-mounted steam generator rated at approximately 50 BHP. This unit will produce 1500 lb/hr (10.5 mole/s) of steam at pressures of 50 psia (350 kPa) adequate to supply the process. A portion of this steam flow will be available for vaporizing liquid oxygen for process purposes. The oxygen will be delivered to the site in liquid form via transport trailers. A trailer-mounted vaporizer will be used to supply the required flow of gaseous oxygen to the system. This unit will be either steam or electrically heated.

Both gases will be supplied to the process through flow control systems using standard control valves and orifice flow metering.

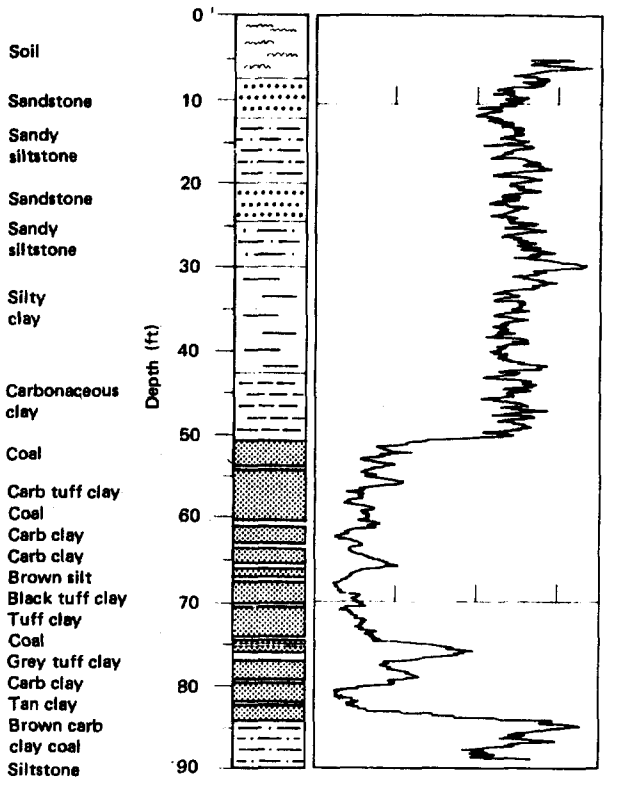

FIG. 28. Large block test areas stratigraphy. (1 ft = 0.3 m.)

Remote and automatic control of the system will be available from a control facility located at a convenient distance from the coal seam face.

Process Wells. The injection wells will consist of horizontal channels drilled into the coal face. These boreholes will be cased over a distance of at least 20 ft (6 m). Wellheads will be assembled to the surface (front) end of the well casing.

Each drilled channel beyond the end of the casing point will serve as the main path for development of the gasification channel and growth of the cavity. These channels will communicate directly with the base of the production (exhaust) wells as shown in Figs. 26-27.

Production wells will be drilled and cased from the surface to within the coal seam. Each well will be drilled through the casing point to the base of the coal seam to intersect with the horizontally drilled channel. Exhaust gas piping will be assembled to the wellheads attached to each production well casing string.

Exhaust Gas System. Production gas flowing from each of the six production wells will be manifolded together into a common stream to accommodate back-pressure control and flow metering. Redundant, parallel flow metering stations will be used to provide for wide fluctuations in flow and to accommodate on-line replacement of orifice plates, etc.

The product gas will be disposed of through an incinerator. This is an induced-draft unit with the gas and combustion air introduced through nozzles in the base of the 30-ft (9-m) refractory lined combustion stack. This unit is designed to burn approxiately 3,000 cfm (60 mole/s) of gas of the quality 120-180 Btu/scf (105-160 kJ/mole) presumed to be generated from the experiments.

Water System. A source of cooling water will be made available at the site to provide for a series of requirements. The process wells will be equipped with cooling water ports through which cooling water will be introduced if process well temperatures indicate the need for control. This system will be used to quench the gasification process at the time gasification is to be terminated. The water will also be used to provide boiler feedwater for the steam generator.

Temperature Monitoring. The most significant diagnostic variable that will be monitored during the tests will be temperatures in the various gas streams and within the burn zone. These temperatures will be monitored using metal-sheathed thermocouples. Most of these thermocouples will be imbedded in the coal seam either through separately drilled channels or attached to process well casing or well internals, as shown in Figs. 26-27. Temperature measurements will be monitored in the control facility and will be used to continuously observe growth of the gasification reaction zone cavity.

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