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RESULTS OF THE FOURTH HANNA FIELD TEST

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ABSTRACT

The second phase (Hanna IVB) of a coal gasification experiment near Hanna, Wyoming, was completed in September 1979. The experiment attempted to link and gasify coal between process wells spaced 34.3 meters apart. Intermediate wells were positioned between the process wells so that the link could be relayed over shorter distances. Reverse combustion linking was attempted over a 22.9-meter and a 11.4-meter distance of the total well spacing. Thermal activity was generally noted in the upper 3 meters of the coal seam during the link. Two attempts to gasify over the 34.3-meter distance resulted in the propagation of the burn front at the coal overburden interface. Post-burn evaluation indicates "fractures" as major influencing factors of the combustion process.

INTRODUCTION

Since 1972, the Laramie Energy Technology Center (LETC) has been conducting underground coal gasification (UCG) experiments near Hanna, WY. The first experiment (Hanna I), conducted from March 1973 through February 1974, was run to assess the feasibility of UCG process on subbituminous coal. The Hanna II experiment was conducted in three phases during 1975 and 1976 and dealt with the effects of directional permeability, pneumatic linking, and an attempted line drive reverse combustion. The Hanna III experiment, conducted in 1977, was designed to provide information on the potential impacts of UCG on ground water.

The Hanna IV experiment was the most ambitious UCG experiment fielded in the United States.[1-2] The experiment was aimed at the near-term commercialization of UCG and the first step to a multimodule semiworks plant. The original objectives for the experiment included gasification of a 30.5-meter link while creating a second 45.7-meter link. The entire 76.3-meter link path was to be gasified in order to verify the sweep width to well spacing relationship derived from model calculations.[3] In addition, high volume production was to be sustained for a time period of approximately 90 days.

Difficulties were encountered at the beginning of the Hanna IV experiment[2] and persisted throughout its duration. The well pattern for the Hanna IV experiment is given in Fig. 1. The Hanna IVA experiment was an attempt to link and gasify the 30.5-meter distance between wells 1 and 2. During Hanna IVA, poor well completions led to excessive water influx into wells 1 and 3 as well as unusually good air communication between these wells, indicating that communication between these wells was through the overlying aquifer and not the coal seam.[4] This also contributed to poor communication between wells 1 and 2. The poor well

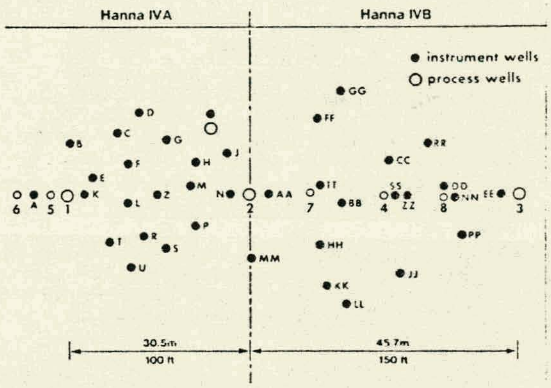

Figure 1. - Modified Hanna IV Well Pattern

completions and possibly poor alignment of wells with respect to the directional permeability of the coal seam led to a lack of directional control for links that were initiated at or below lithostatic pressure. The linking and gasification between wells 1 and 2 (Hanna IVA) and the difficulties encountered have been previously described,[1-2] as well as the resulting override gasification and the attempts to remedy the override condition.

The modifications of the Hanna IV site in order to gasify the remaining 2-3 (Hanna IVB) side of the pattern have been discussed.[4] The content of this paper deals with the linking and gasification from wells 3 to 7, which has been referred to as the Hanna IVB experiment. The description of the events which took place during this experiment as well as interpretation of the results as a function of the geologic features of the Hanna IV site are presented.

EXPERIMENTAL SITE

The Hanna IV site and its position with respect to the Hanna I site, which is 100 meters to the east, are given in Fig. 2. The Hanna IVB

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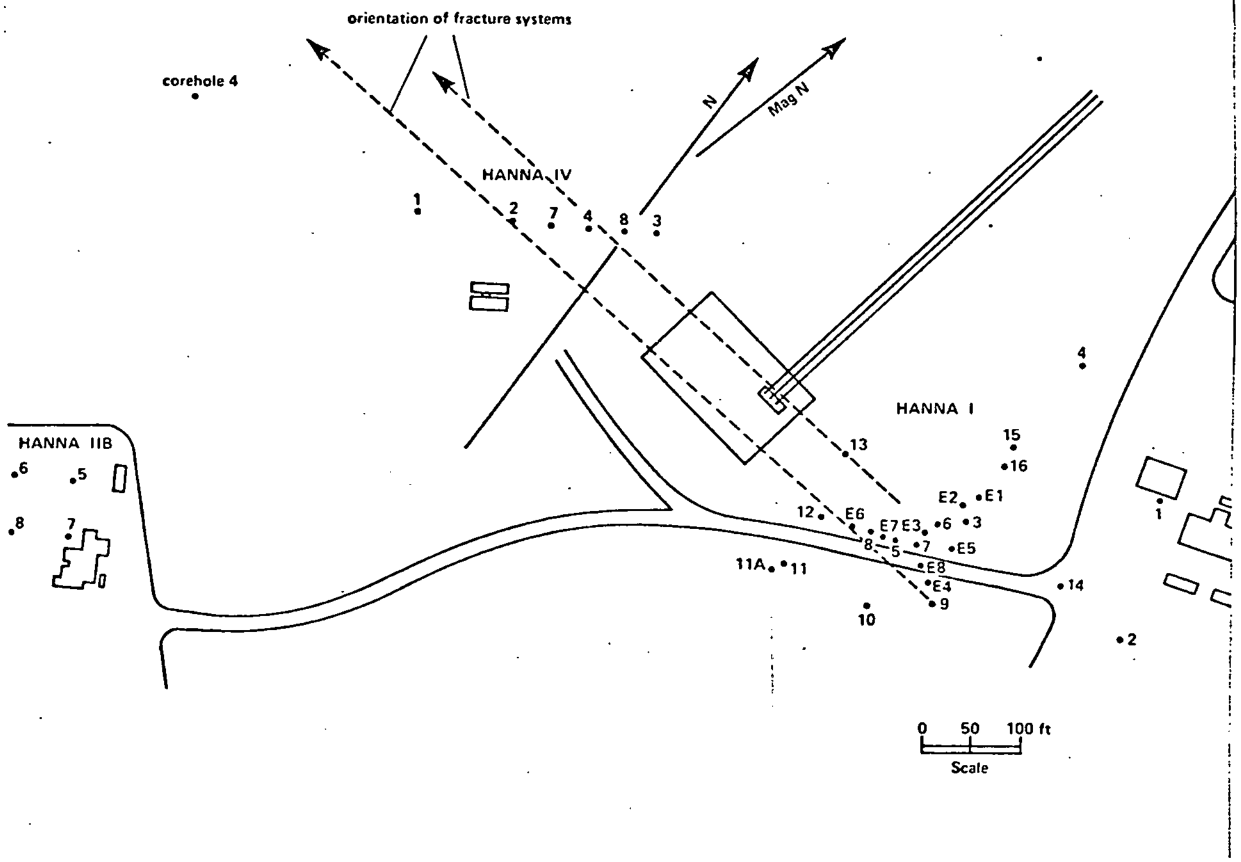

Figure 2. - Hanna Well Pattern

gasification experiment utilized the Hanna I coal seam, which is 10 meters thick and at this location lies at an average depth of 98 meters, dipping to the northeast. Initially, the Hanna I coal seam was considered to be a subbituminous coal; however, has recently been reclassified as a bituminous, high volatile coal.

Well Completion and Surface Piping

After the difficulties encountered in Hanna IVA,[1-2] well 2 was abandoned because of casing damage and the consumption of coal around the wellbore. Eight new wells were drilled prior to initiating Hanna IVB. Well 7 was designated the main production well while well 8 was to be used as an injection well for relaying the link from 7 to 3. Figure 1 gives the location of these two wells in addition to the five new instrument wells (RR, SS, TT, PP, and MM). Also, a new subsidence well, ZZ, was drilled and instrumented. Because the completion of well 3 was suspect with possible direct communication with the overlying aquifer, the well was redone with a 15.2 cm ID casing placed in the original 30.5 cm ID casing. The entire diagnostic analysis and repair of well 3 has been fully described elsewhere.[4]

The elaborate surface piping system during Hanna IVA was replaced with a simpler one for the Hanna IVB test. The original piping showed signs of fatigue and was continually in need of repair. For this reason, a new piping system was fabricated and installed. The new system consisted of two production lines, a main production line, and an emergency bypass line, running from well 7. The lines were straight pipes with flares at the end of each line. The piping systems and the flares were not anchored to the ground, except at well 7, and were placed on rollers to allow for thermal expansion. The thermal expansion of the well casing was accommodated by the use of expansion bellows installed vertically at the wellhead.

Instrumentation and Data Acquisition

The instrumentation, fielded by Sandia National Laboratories,[5] was designed to obtain diagnostic information about the UCG process and to detect and monitor the size, location, and progression of the reaction zone. The thermocouple wells were located such that only a few would survive the experiment, and thereby define gasification zone boundaries at the widest point of areal sweep. Remote monitoring of the reaction zone was attempted using passive acoustic and electrical resistivity instrumentation.

The Hanna IV data acquisition system was an HP 21MX minicomputer which not only collected data, but also provided real time analysis and automated air injection control. Thermocouple readings and flow data were collected at 5-minute intervals, while gas analyses of the process stream were read approximately every half hour. Because of the difficulties in detecting a thin layer of coal tar on water, the tar/water collection system was not operated by the computer as had been attempted for Hanna IVA. The data were taken by an operator and manually entered into the computer. All gas volume calculations were based on a temperature of 15° C and 101 Kpa.

OPERATION AND RESULTS

Air Flow Tests

Initial air flow tests from well 3 to well 7 indicated that a direct 34.3 meter link between these two wells would be difficult. Injection into well 3 at the planned linking injection pressure of 2400 Kpa produced only 0.2 m^3/min of flow at well 7. The general consensus was that this flow would not sustain reverse combustion. A scheme to sequentially relay the link in 11.4-meter stages from well 7 to wells 4, 8, and 3 was considered. A series of flow tests were performed to determine the feasibility of this linking scheme and Table I summarizes the results of these tests. It should be noted that large air losses were experienced in all of the tests except between wells 8 and 3 as shown in the last column of Table I.

Based on these test results, well 4 was bypassed as a relay point between wells 7 and 8, because it did not have sufficient communication with both well 7 and well 8. Low production flows were observed between well 4 and wells 7 (0.26 m^3/min) and 8 (0.17 m^3/min). Direct communication between wells 8 and 7, however, produced a flow at well 7 of 0.74 m^3/min, three times the flow produced between well 4 and wells 7 and 8. A new linking scheme was planned which would be to first link the 22.8 meters using well 8 as an injection well, then link the remaining 11.4 meters using well 3 for injection.

Monitoring the Hanna I field site revealed a substantial pressure buildup in well 13 (1035 Kpa) which appeared to indicate the air losses were moving in the southeast direction from Hanna IV to Hanna I. The cause of the air movement out of the test site is believed to be a fault zone between wells 4 and 8, which will be discussed later.

Ignition and Linking

Ignition was accomplished on April 20, 1979 (Julian date 110), at approximately 11:00 a.m., using an electrical ignition system. The bottom of the ignition well (well 7) was prepared by floating down a 1-meter coal pack. The water column in the well was then pneumatically removed and warm air allowed to circulate through the coal pack for 24 hours. A 1500-watt calrod heater placed in a small cloth bag packed with charcoal was then lowered to the coal pack. The calrod heater survived for only 10 minutes, but ignition was confirmed by thermal responses in the wellbore. Two thermocouples, one at the 1 meter level and the other at the 4 meter level from the bottom of the coal seam monitored the vertical position of the fire zone.

A high temperature at 4 meters would trigger cooling water addition through a 1.9 cm sparge tube to cool the casing in the upper section of the coal seam. It was believed that maintaining the hot zone at the coal seam base would enhance the probability of starting a low link. Also, in the case of a bad well completion, it was believed that this system would retard vertical movement of the fire zone up the outside of the casing.

Ignition well temperature during startup are plotted in Fig. 3. The cooling system maintained the upper coal seam casing temperature

TABLE I. - Preignition air acceptance test for Hanna IVB gasification experiment

Injection well(s)	Production well	Injection flow m^3/min	Production flow m^3/min	Recovery percent
4	7	6.94	0.26	4
8	7	14.74	0.74	5
3,4,8	7	13.88	1.05	8
8	4	10.63	0.17	2
3,8	4	10.34	0.21	2
3	8	2.83	0.50	17.5

Injection pressure maintained at 2410 Kpa

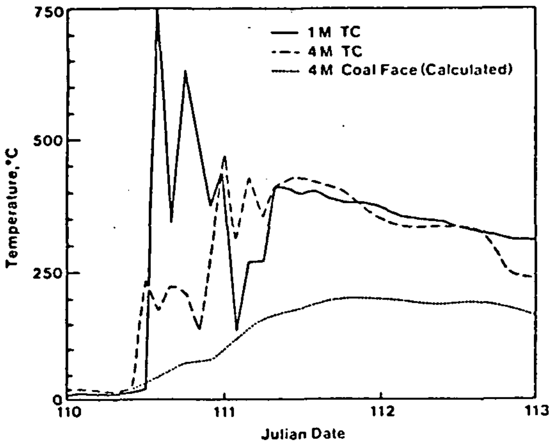

Figure 3. - Ignition well temperatures

below the predetermined temperature of 250° C for 12 hours when a high temperature excursion at the 4-meter level occurred. Attempts to lower this temperature failed and cooling water addition began to cool the 1-meter level faster than the 4-meter level. Subsequent thermal analysis of the 4-meter level predicted that the heat conducted from the well casing into the coal in this vicinity was not high enough to cause ignition. The calculated coal face temperatures for this level is shown in Fig. 3 and indicates that autoignition caused by a hot well casing probably did not take place. The temperature excursion was probably from a fire front moving up the outside of the well casing.

In order to link between wells 8 and 7, air was initially injected into wells 3, 4, and 8, then switched solely to well 8. Linking to well 8 was completed in 10 days (JD 120). Thermal responses during this linking phase were observed in only two wells, BB and SS. In well BB two distinct thermal responses were noted, one at 2.7 meters and the other at 7 meters from the bottom of the coal seam. The responses observed in well SS were in the upper half of the coal seam. Production flows during the linking phase between wells 7 and 8 were maintained at 2.83 m^3/min, while the injection pressure was kept below lithostatic pressure.

After one day of forward combustion, injection was switched to well 3 to begin the second phase of linking. Problems in maintaining gas quality and production flow were immediately encountered, and the injection pressures had to be raised above lithostatic to produce a significant production flow. The link of only 11.4 meters between wells 8 and 3 was completed after 73 days (JD 193).

Thermal responses during the second linking phase were mainly confined to an area north of the injection/production well line. Instrument wells RR, CC, and FF recorded temperature excursions in the upper half of the coal seam. Wells DD and NN which are just north and east of well 8 respectively indicated thermal responses only after the experiment was well into the second linking phase (JD 130). Temperature responses in well EE, 3 meters west of well 3, were first recorded on JD 178, however, the link was not completed for another 15 days. Table II summarizes the linking conditions and results obtained during the two linking phases.

Gasification

The coal between wells 3 and 7 was gasified in two stages, well 3 to well 7 and well 8 to well 7. The results of these gasifications are presented in Table III. The duration of the 3-7 burn was 6 days (JD 209-216) and was terminated when a gas leak developed in the production system. Thermal responses were observed in wells EE, RR, CC, and BB between 6.1 and 7.6 meters from the bottom of the coal seam. The rapid movement of the thermal front to well BB and the vertical location in the coal seam are interpreted to indicate that an override condition existed.

The maximum production rate and heating value during this gasification phase was 1190 m^3/min and 7.76 MJ/m^3. The heating value was at its maximum at the start of gasification and declined steadily to 5.05 MJ/m^3 at termination. A maximum energy production rate of 2.11 x 10^9 joules/min occurred at JD 214.

Generally, the rapid movement of the combustion front toward the production well (well 7), indicating an override gasification, would have resulted in the termination of the experiment. However, the thermal responses in wells RR and CC indicate that the gasification did not burn toward wells DD or 8, but to the north of the 3 to 7 well line. There was no evidence

TABLE II. - Operating conditions for the 7-8 link and the 8-3 link

	7-8 link	8-3 link
Average heating value	4.53 MJ/m^3	3.56 MJ/m^3
Product gas flow	2.83 m^3/min	1.20 m^3/min
Injection pressure	2.07-2.41 Mpa	2.75-2.82 Mpa
Backpressure	0.34 Mpa	0.014-0.034 Mpa
Average injection flow	11.9 m^3/min	6.18 m^3/min
Coal consumed/day based on 50% carbon recovery	1097.7 kg	417.3 kg
Nitrogen recovery	0.24	0.19

TABLE III. - Summary of results of the first and second phases of the Hanna IVB gasification

	3-7 Gasification	8-7 Gasification
Length of burn	6 days	15 days
Maximum injection flow	3.02 m^3/sec	1.53 m^3/sec
Average injection flow	1.79 m^3/sec	0.826 m^3/sec
Maximum production flow	5.28 m^3/sec	2.36 m^3/sec
Average production flow	4.25 m^3/sec	1.53 m^3/sec
Maximum heating value	7.45 MJ/M^3	5.96 MJ/M^3
Average heating value	5.96 MJ/M^3	4.84 MJ/M^3
Total coal consumed	6.89×10^5 kg	6.94×10^5 kg
Maximum daily coal consumption	9.07×10^4 kg	4.39×10^4 kg
Average daily coal consumption	7.26×10^4 kg	2.86×10^4 kg
Total energy produced	6600 MJ	8955 MJ

of any change in the thermal response of well DD, again indicating that the link from wells 8 to 7 was independent of that from wells 3 to 7. For these reasons it was felt that further attempts to gasify from well 3 would be fruitless and at this time it was decided to attempt a gasification from well 8 which apparently was unaffected by the 3 to 7 gasification.

Forward gasification was initiated from well 8 on JD 246 and terminated 16 days later on JD 262. Injection flow was ramped incremently to a maximum of 255 m^3/min starting at 85 m^3/min and increasing in 25 m^3/min intervals. Maximum production rates were 425 m^3/min and 5.3×10^8 joules/min. The heating value during the first 10 days remained steady at nearly 5.24 MJ/m^3. It then began a steady decline, and rapidly decreased on the day before termination. Thermal responses were noted in wells DD, NN, EE, CC, RR, SS, BB, and TT at the upper half of the coal seam, indicative that an override was evident, and the experiment was terminated. The rapid decrease in the heating value as well as thermal responses in wells CC and RR would indicate that the gasification front burned into the wells 3 to 7 override cavity.

DISCUSSION

Three dimensional link propagation through a coal seam is dependent on air flow characteristics through the seam which in turn are dependent on certain geological features. At the Hanna site there are three geologic features which control air flow: cleating, horizontal permeable zones, and faulting. The interaction of these features can account for the air flows within the coal seam. Intrusions into the seam by such activities as drilling, well completions, and hydrofracing also cause localized distortions in these features with corresponding distortions in flow patterns.

It has been shown that the anisotropic permeability in coal is controlled by cleating.[6] Four cleat sets have been identified in the coal of the Hanna Basin:[7]

Set A	N70° - 65°W
Set B	N40° - 30°W
Set C	N23° - 25°E
Set D	N60° - 70°E

Fracture orientation similar to cleat sets A, C, and D were observed with an impression packing taken in well 3 of the Hanna I site.[8] A fracture oriented at N16°W was found in this well. This fracture could not be identified with the above cleat sets. Cleat sets C and D were also observed in well 1 of the Hanna II site.[9] Air transmissivity tests at Hanna II indicated the major flow to be along the D cleat direction. Air recovery was approximately 20 percent in this direction compared to 1 percent in the A cleat direction. All subsequent field tests at Hanna were oriented along this direction of higher permeability.

Examination of cores taken from the Hanna site indicate that there are three horizontal permeable zones in the coal seam. These zones consist of broken coal interbedded with stringers of shale, mud, and sandstone, and are depicted in Fig. 4. Spinner logs confirm the horizontal permeability of these zones with a region of high permeability at 96-98 meters from the surface, which is near the top of the coal seam. Localized regions of air flow occur from 99.7 meters to 101.2 meters and at 104.5 meters. These are illustrated in Fig. 5. Air flow tends to occur in the upper portion of these permeable zones at the interface with the overlying impermeable material. The Hanna IVB experiment confirmed link movement along these permeable zones. Figure 6 illustrates that thermal responses at the various instrument wells coincides with the flow path observed in the spinner logs.

By controlling the combustion zone during ignition it was hoped to isolate the reverse link combustion front in the lower permeable zone. The combustion front, once established in this zone, should remain in the zone except when a natural or manmade disruption in horizontal isolation occurs. In Hanna IVB, both manmade and natural disruptions were encountered during linking.

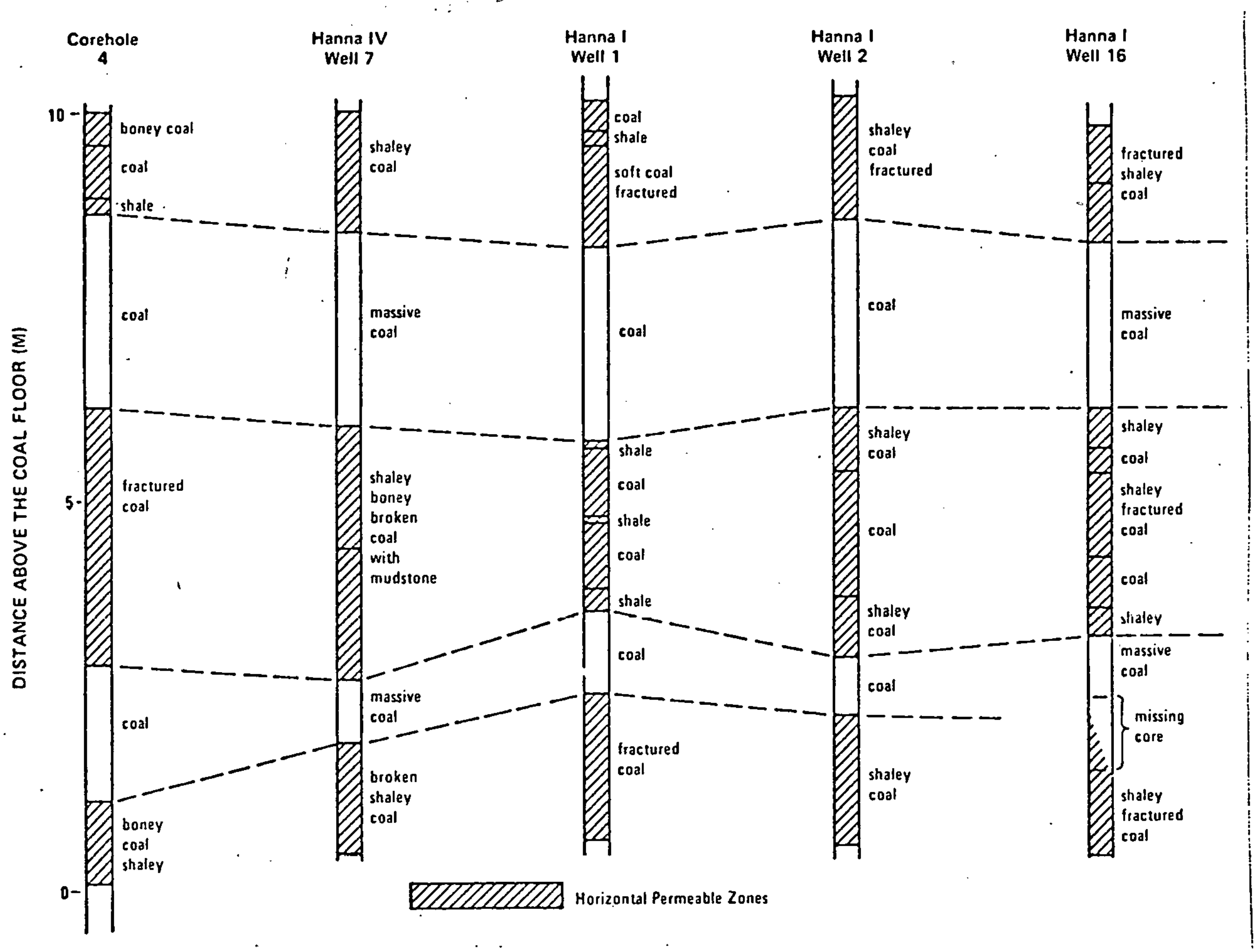

Figure 4. - Cross Section of Wells at Hanna

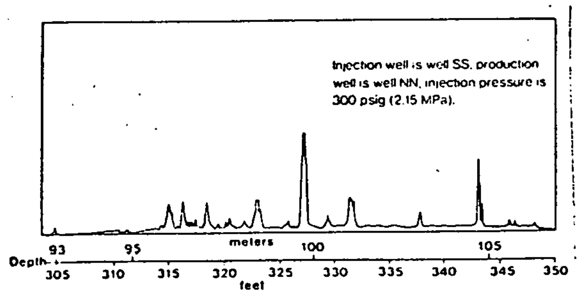

Figure 5. - Spinner Log of the Location of Various Air Flow Paths Relative to Wellbore Position

Thermal responses at and near the ignition well showed rapid vertical movement of the combustion front to nearly the top of the coal seam. The thermal excursion at the 7-meter level of well BB which is within 3 meters of the ignition well showed either (1) rapid vertical movement of the combustion front or (2) coal face ignition at that level of the ignition well due to conductive heat transfer up the well casing. However, thermal analysis of the temperature excursion at the 4-meter level in the ignition well indicated that the coal face would not be heated high enough by conductive heat to ignite (Fig. 3) and, therefore, the excursion was probably due to a combustion front moving up the outside of the casing. This would also explain why the 1-meter level was cooling faster than the 4-meter level after the large temperature excursion at this level.

Generally, the cleat systems and zones of horizontal permeability regulate air flow within a specific area; however, when a fault bisects this area the fault then becomes the dominant feature. Faulting will also disrupt the horizontal isolation of permeable zones in the coal seam. The trend of faults in the Hanna Basin is in a northwest-southeast direction which is diagonally across the Hanna IV pattern as indicated in Fig. 8. Subsurface

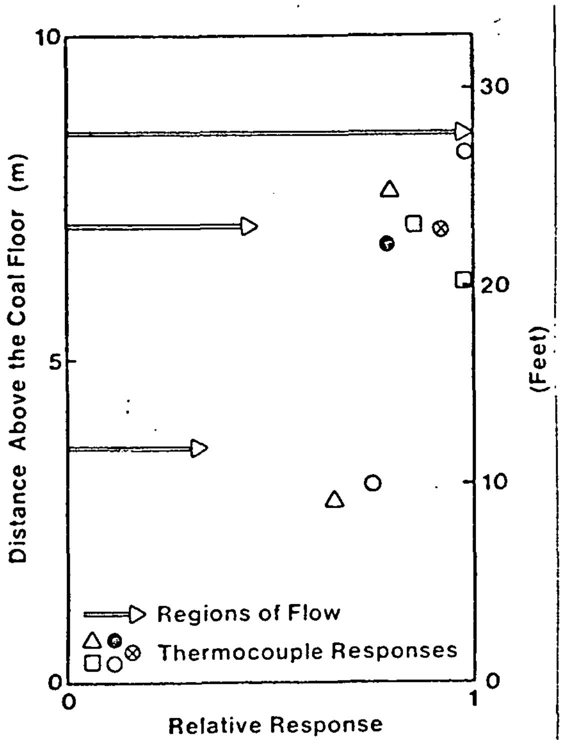

Figure 6. - Thermal Response and Relative Logging Response

elevations analysis at the process wells indicate that there is a fault with a 1.5 to 3 meter vertical displacement that intersects the Hanna IV pattern at approximately a 45° angle between wells 4 and 8.[10] When the line of this fault is extended to the southeast, the line crosses the Hanna I pattern near well 13. Injection flow tests confirmed air movement along this zone. Well 13 of Hanna I responded to air injection into well 3 of Hanna IV with a pressure buildup of 1035 Kpa while injection pressure was held at 2410 Kpa. This pressure increase occurred even though well 13 is approximately 90 meters to the southeast of well 3. Air flow tests indicate that the air loss from Hanna IV occurred between wells 4 and 8. This corresponds with the location of the fault zone and it is believed that many operational difficulties encountered with Hanna IVB were the result of this fault zone.

The faulting between wells 8 and 4 probably influenced the high link by establishing air flow in the upper horizontal permeable zones. Vertical communication between permeable zones at the ignition well would not by itself cause upward movement of the combustion front. Air flow must already be established higher up in the coal seam for the combustion front to propagate there. Since air was introduced only into the bottom third of the coal seam at the injection well, horizontal flow isolation must have been breached by either poor injection well completion or geologic disruption caused by faults.

The combustion front during the 7 to 8 link appeared to stop propagation near instrument well DD and thus did not proceed all the way to well 8. This interpretation is supported by attempts to produce well 8 while injecting in well 3 after the communication between wells 7 and 8 had been established. The production gas was essentially air with no combustion gases. It appears that the combustion front burned through into the fault and at that point the reverse combustion became unstable and changed from reverse to forward combustion. A sudden reversal similar to this was reported in the Hanna II experiment.[11] Once the combustion front had burned into the fault system, it did not burn down the fracture toward well 8, but remained at the point of entrance to the fault system. This behavior is similar to that seen in simulated laboratory linking tests where a combustion front could not be drawn down an open channel until the oxygen content of the injection air had been increased to 35 percent.[12] For this reason, it appears that air injected into well 3 arrived at well 8 and did nothing more than slowly propagate combustion near well DD with little movement of the combustion front.

The long time required for the link to propagate from well 8 to well 3 might also be explained by the discussion in the previous paragraph. Because the combustion front was not advancing from the area around well DD, a new link originated from the area around well 7 and this link finally arrived at well 3. The latter link followed a different path than the first link as indicated by the thermal responses observed in instrument wells RR and CC.

The resulting links of the Hanna IVB experiment were undoubtedly high in the coal seam as indicated by the thermal responses observed during the linking. The gasification of these links resulted in the expected override conditions that caused premature termination of Hanna IVB. If good gasification had occurred low in the seam, a more effective usage of resource and a longer gasification would have resulted.

SUMMARY

The Hanna IVB field test provided much insight into influence that geologic features have on in situ coal combustion. The influence of these faults, permeable zones, and cleats, on the air flow patterns can drastically change the overall results of a gasification experiment and should be studied further.

The overall results of Hanna IVB were discouraging because of the rapid decline in the heating values for the production gas and the amount of coal gasified. With more complete geologic characterization prior to experimentation and proper well completions, it is believed that most of the subsurface operational problems encountered during Hanna IV could have been avoided.

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Reference to specific equipment does not imply endorsement by the Department of Energy.

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