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INSTRUMENTATION AND PROCESS CONTROL

DEVELOPMENT FOR IN SITU COAL GASIFICATION

EIGHTH QUARTERLY REPORT: SEPT. THROUGH NOV. 1976

MASTER

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INSTRUMENTATION AND PROCESS CONTROL DEVELOPMENT
FOR IN SITU COAL GASIFICATION

Eighth Quarterly Report: September through November 1976

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HIGHLIGHTS

The Second Hanna In Situ Coal Gasification Experiment ended on July 31, 1976. After limited posttest monitoring, Sandia Laboratories ended their field activities in mid-September. The past quarter's activities have focused upon the reduction and analysis of the experimental data. Planning has been initiated for an instrumentation effort to be fielded on the Hanna IV experiment to begin in the spring. (p. 5)

Analysis of thermal data has yielded additional detail on the linkage and gasification processes. Specific information includes: the size, temperature, and specific location of the linkage path, a physical description of the growth of the gasification region, and the profile and extent of the outer boundaries from thermal responses measured outside of the reaction zone. (p. 12)

Preliminary source locations for discrete acoustic signals observed during gasification are in the overburden and appear to occur above those regions where high temperatures occur at the top of the coal seam. (p. 22)

A field data acquisition system, built around a minicomputer and capable of in-field prompt reduction and presentation of data, has been designed and is being assembled. It will be an integral part of all instrumentation techniques to be fielded on Hanna IV. (p. 27)

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Previous quarterly reports for this program are:

Instrumentation and Process Control Development for In Situ Coal Gasification:

First Quarterly Report, December 1974 through February 1975, Sandia Laboratories Report, SAND75-0200, April 1975.

Second Quarterly Report, March through May 1975, Sandia Laboratories Report, SAND75-0366, June 1975.

Third Quarterly Report, June through August 1975, Sandia Laboratories Report, SAND75-0535, October 1975.

Fourth Quarterly Report, September through November 1975, Sandia Laboratories Report, SAND75-0669, January 1976.

Fifth Quarterly Report, December 1975 through February 1976, Sandia Laboratories Report, SAND76-0191, April 1976.

Sixth Quarterly Report, March through May 1976, Sandia Laboratories Report, SAND76-0362, July 1976.

Seventh Quarterly Report, June through August 1976, Sandia Laboratories Report, SAND76-0612, October 1976.

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I. INTRODUCTION

This is the eighth quarterly report for Sandia Laboratories' program on Instrumentation and Process Control Development for In Situ Coal Gasification. This report summarizes program activities between September 1 and November 30, 1976 which have been conducted primarily in conjunction with the Laramie Energy Research Center's (LERC) underground coal gasification program and field experiments being conducted near Hanna, Wyoming.

The Second Hanna Experiment (Hanna II) has been completed. Sandia's major instrumentation effort was associated with Phases 2 and 3 which were fielded in the early Fall, 1975 and conducted April through July 1976. Sandia's field operation at Hanna is presently demobilized. Activities now focus upon analysis of the extensive Hanna II experimental data in order to contribute to the understanding of the in situ process and to critically evaluate the different instrumentation techniques which were fielded. Planning of the instrumentation effort for a subsequent gasification experiment in 1977 has been initiated.

Successful development of any in situ fossil energy technology will require both (a) a thorough understanding of the chemical and physical mechanisms of the in situ process and its relation to the resource and geology and (b) positive process control to produce a product of consistent quality and quantity with efficient resource utilization. The absence of this technical understanding and positive process control has been a major contributing factor which has prevented the widespread development of in situ coal gasification despite world-wide interest and investigation over the past hundred years. This Sandia program for Instrumentation and Process Control Development directly addresses this factor.

The objectives for this program are: (1) to evaluate instrumentation techniques as they apply to in situ coal gasification, (2) to obtain diagnostic information on the chemical and physical mechanisms associated with this remote process in order to further its understanding, (3) to develop and evaluate remote (and thus more versatile and economical) monitoring techniques and establish their correlations with the process (4) to develop analytical models for the purpose of process identification, instrumentation development and design, and process modeling, and ultimately, (5) to develop a process control system utilizing remote monitoring techniques to optimize the recovery of energy by in situ coal gasification. Activities during the past quarter contributing to these objectives will be described in this report.

Finally, this program is aimed at the detection, monitoring, and the control of a combustion process occurring underground. Thus, results from this program should have direct application to the development of in situ combustion recovery techniques for other fossil energy resources such as oil shale, tar sands and petroleum.

II. INSTRUMENTATION AND FIELDING SUMMARY (D. A. Northrop, 5732 and J. A. Beyeler, 1123)

The Second Hanna Experiment has been completed. Phase 1, a site characterization and preliminary gasification test, was conducted between January and August, 1975. Construction and fielding for Phases 2 and 3, the major parts of the experiment, were accomplished between August and November, 1975. Phase 2a, the creation of a permeable path or link by reverse combustion between a pair of wells to be used in Phase 3, was conducted during December, 1975. Phase 2b, reverse combustion linkage and gasification between a pair of wells, was conducted during April and May, 1976. Phase 3, evaluation of a line drive concept and extensive gasification between a pair of wells was conducted during June and July, 1976.

Detailed descriptions of all aspects, results, and initial interpretations of the recent phases can be found in a series of papers prepared by Laramie Energy Research Center personnel which will appear in the Proceedings of the 2nd Underground Coal Gasification Symposium, Morgantown WV, August 1976.* Among the significant findings from this test are:

- (a) the width of the gasification zone during Phase 2 was approximately 60 ft which was equal to the well spacing and twice the seam thickness,
- (b) total amount of coal gasified during Phases 2 and 3 was 6700 tons as compared with 4600 tons of coal in place within the 60 x 60 foot well pattern indicating outstanding sweep efficiency,
- (c) linkage and initial gasification occurred near the bottom of the coal seam with no apparent tendency for thermal override, and
- (d) while process parameters were intentionally varied during the experiment, significant gas production was obtained for stable periods of several weeks: greater than 100 tons of coal per day were gasified resulting in a potential power generation of 6-7 MWe.

*These papers were listed in the Seventh Quarterly Report.

Sandia's major instrumentation effort was associated with Phases 2 and 3 of the Second Hanna Experiment. Instrument fielding details and specific sensor locations were given in the Fourth Quarterly Report (p. 8-17). A summary of the instrumentation, well locations, and a dated activity summary are presented for reference in this report in Table I, Figure 1, and Table II, respectively.

Although Hanna II was terminated on July 31 (Day 213), limited posttest monitoring was performed into September. The last instrumentation to be terminated were the tilt, displacement and thermal measurements on September 14 (Day 258). Surviving thermocouple circuits were transferred on that data to LERC's on-site computer for continued monitoring of the cool-down period. Sandia demobilized its field effort at Hanna by the end of the month. This ended 21 months of essentially continuous activity at the site.

Table I
SUMMARY OF INSTRUMENTATION FIELDIED FOR PHASES 2 AND 3 OF THE HANNA II
UNDERGROUND COAL GASIFICATION EXPERIMENT

INSTRUMENTATION WELL	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	TOTAL
LOW TEMPERATURE LEVELS ⁽¹⁾	10	9	10	10	8	9	9	10	10	10	10	10	10	7	9	141
HIGH TEMPERATURE LEVELS ⁽²⁾		3	3		3	3										12
RESISTIVITY PROBES ⁽³⁾	3	3	3	3	3 ⁽⁴⁾	3 ⁽⁴⁾	3	3	3	3	3	3	3	3	3	48
GEOPHONES	10	10	10	10	10	10	10 ⁽⁵⁾	10	10	10	10	10	10	10	10	150
GAS SAMPLING CANISTERS		1	1	1	1	1	1		1	1					1	9
DOWNHOLE PRESSURE TRANSDUCERS			1			1	1									3
SURFACE PRESSURE TRANSDUCERS		1	1	1	1	1	1		1	1					1	9
TILT METERS		2	2			2		2	2	2	2					14
DISPLACEMENT LEVELS			4		4		4									12
																398
PLUS SURFACE: GEOPHONE ARRAY (20 FT DEPTH)																15
RESISTIVITY PROBE ARRAY																81
TOTAL																494

- NOTES: (1) UP TO SIX-FOLD REDUNDANCY AT MOST LEVELS PLUS RESISTANCE AND NOISE MEASUREMENTS GREATLY INCREASE THE TOTAL NUMBER OF THERMAL CHANNELS AVAILABLE.
- (2) DIFFERENT MATERIALS FIELDIED FOR EVALUATION.
- (3) THREE PROBES ALSO FIELDIED IN SHOT-WELL, 31.
- (4) HIGH TEMPERATURE SENSORS AND CABLES FIELDIED IN THESE WELLS.
- (5) DIFFERENT GEOPHONE SPACING TO MEASURE VERTICAL ATTENUATION.

Table II
ACTIVITY SUMMARY - PHASE 2a

<u>Day (1975)</u>	<u>Date (1975)</u>	<u>Activity</u>
329	November 25	Begin air injection in Well 7 with production at Well 8.
337	December 3	Ignition in Well 7.
338	December 4	Remove heater. Switch injection to Well 8 with production at Well 7.
345	December 11	Injection pressure drop; linkage; front reversal.
345-352	December 11-18	Period of low injection flows at moderate injection pressures to increase permeability between wells.
353	December 19	Blockage removed by pressure surges. High permeability attained; high injection flows at low pressures demonstrated. Air injection halted immediately to terminate Phase 2a.
40 (1976)	February (1976)	Water injected into Wells 7 and 8 to further cool region.

ACTIVITY SUMMARY - PHASE 2b

<u>Day (1976)</u>	<u>Date (1976)</u>	<u>Activity</u>
88	March 28	Begin air injection in Well 5 with production at Well 6.
94	April 3	Ignition in Well 5 at low heater temperature.
96	April 5	Remove heater. Switch injection to Well 6 with production at Well 5.
105	April 14	Injection pressure drop; linkage; front reversal.
105-114	April 14-23	Period of low injection flows and pressures.
114-121	April 23-30	Period of moderate injection flows and pressures.
124	May 3	Reversed flow for several hours. High permeability attained; high injection flows at low pressures.
124-129	May 3-8	Gasification. 1700 cfm injection at Well 6; ~ 2900 cfm production at Well 5.
129-134	May 8-13	Gasification. 2500 cfm injection at Well 6; ~ 4300 cfm production at Well 5.
134-151	May 13-30	Gasification. 3500 cfm injection at Well 6; ~ 5800 cfm production at Well 5.
151	May 30	Terminate Phase 2b. Replumb for Phase 3.

ACTIVITY SUMMARY - PHASE 3

<u>Day (1976)</u>	<u>Date (1976)</u>	<u>Activity</u>
152	May 31	Injection into Wells 7 and 8 with production at Wells 5 and 6.
155	June 3	Apparent linkage; high temperatures at Well 6 and instrumentation Well H.
156-173	June 4-21	Period of variable injection parameters and flow configurations results in decision to gasify between Wells 7 and 8.
174-182	June 22-30	Gasification. 2500 cfm injection at Well 8; ~ 4800 cfm production at Well 7.
182-189	June 30-July 7	Gasification. 3500 cfm injection at Well 8; ~ 6600 cfm production at Well 7.
189-212	July 7-30	Gasification. 4500 cfm injection at Well 8; ~ 7500-8300 cfm production at Well 7.
213	July 31	Halt air injection at 0010 hrs. Terminate Phase 3.

Figure 1. Well locations for Phases 2 and 3 of the Hanna II in situ coal gasification experiment. Numbers identify injection/production wells; letters identify instrumentation wells; S1 and S2 are cased wells for the induced seismic experiment.

During the week of November 15, 1976, a Vibroscis test was conducted by Sandia with a unit supplied and operated by Seismograph Service Corporation. This was a preliminary test to evaluate whether such signal processing techniques could be employed in a surface source to downhole sensor configuration for an induced seismic technique. Data were collected by a Sandia van-mounted minicomputer and are presently being analyzed.

Planning has been initiated with LERC for a Sandia instrumentation effort in conjunction with the Hanna IV in situ coal gasification experiment to be conducted in late 1977. (Hanna III will be a small limited gasification test with specific environmental objectives to be conducted by LERC during 1977.) As before, both diagnostic and remote monitoring instrumentation techniques will be fielded utilizing both instrumentation wells within the experimental area and surface probe arrays. Reaction diagnostic techniques include: temperature measurements via branched thermocouple circuitry which

allows for redundancy and data validation, gas canisters and sampling lines providing access to in seam gas samples and pressure measurements and a feasibility test of a time domain reflectometry or slifer-based method to measure subsidence from the seam to surface. Based upon assessment of Hanna II results, development of the following remote monitoring techniques will continue and will be evaluated on the Hanna IV test: (a) both the direct excitation electrical potential (DEEP) and modified Schlumberger (MS) current configurations will be used with a large surface probe array and a probe in each diagnostic well above the coal seam, (b) passive acoustic source mapping by geophone assemblies located in the overburden in selected wells, and (c) an induced seismic technique in a surface source to downhole sensor configuration where both shadowing and reflection will be examined. All instrumentation techniques will use a central minicomputer-based data acquisition system for on-site processing, reduction and display. The development and implementation of this system is one objective of the field effort.

III. TEMPERATURE STUDIES

A. Posttest Thermal Data (S. G. Beard, 5732 and R. P. Reed, 1116)

Since the termination of recording of thermal data by Sandia Laboratories on Day 257, data from the few remaining thermocouples in the overburden and originally at the top of the seam and those in Well K and N outside the reaction zone have been recorded on the LERC on-site computer. Recording of selected temperatures will continue until the LERC computer channels are required for future experiments.

Plots of the thermal data during most of the cooldown period following the termination of air injection on Day 213 are presented in Figure 2. Data for several levels were not recorded during certain periods because either the recording equipment failed or channels were not available to record measurements from the lower priority thermocouples. The fluctuations in all the curves near Day 300 was probably caused by problems in the recording system.

During the time period shown on the plots, the temperatures at the top of the former reaction zone have decreased slowly and those wells in the overburden and outside the reaction zone (Wells K and N) have gradually increased. As a result of possible damage to the thermocouple circuits during gasification and the subsequent reformation of the junctions at higher levels, the locations of the sensing points are not known in several cases; but diagnostic measurements and the characteristics of the curves indicate that the data are representative of the temperatures at the top of the former reaction zone. For example, in Wells B and L, which were located in regions of extensive gasification, identical temperatures are indicated by sensors originally near the top of the seam

FIGURE 2
TEMPERATURE - TIME PROFILES DURING
HANNA II COOLDOWN

THERMOCOUPLES LOCATIONS (FEET)
REFERENCED TO BOTTOM OF 33-FOOT
COAL SEAM.

WELL 8

WELL 7

and approximately 40 feet into the overburden. If these temperatures are valid, and circuit resistance measurements on Day 322 indicate that they are, it appears that the effects of gasification and/or subsidence extended as far as 40 feet into the overburden. In these two wells at the end of the quarter, the temperature 40 feet above the seam was approximately 400°F, but in the other wells it was only 100-200°F.

The rate of temperature decrease in the reaction zone for Days 219-328 was approximately exponential with time constants of -0.0045 day^{-1} to -0.0064 day^{-1} in the Phase 2b area and -0.0073 day^{-1} at Well I in the Phase 3 area. In the Phase 2b wells the temperatures ranged from 720-522°F to 442-257°F during this period. In the Phase 3 region the temperatures decreased from 1160°F to 300-500°F. In Wells K and N, which were a few feet outside the reaction zone, at the end of the quarter the temperatures in the coal seam were slowly approaching maxima of 100-200°F.

B. Analysis of Thermal Data from Phases 2b and 3 (P. J. Hommert and S. G. Beard, 5732)

The analysis of thermal data from Phases 2b and 3 of the Hanna II Underground Coal Gasification Experiment is continuing. Conduction models have been used to define the characteristics of the linkage paths between Wells 5 and 6 and to analyze the responses of sensors located outside the reaction zone in order to define the boundary of this zone.

A constant property analytical solution was used in the preliminary analysis of linkage responses which were presented in the Seventh Quarterly Report (p. 17-21). This model did not allow for the inclusion of variations in thermal properties with temperature or effects due to water vaporization. Numerical finite difference calculations which include these effects have since been performed. Results indicate that for responses below 200°F, the constant property analytical expression,

$$T(r,t) = (T_H - T_A)(a/r)^{1/2} \text{erfc}((r/a-1)/2(\alpha t/a^2)^{1/2}) + T_A, \quad (1)$$

can fit the numerically-generated results within $\pm 5\%$ by adjusting the thermal diffusivity as a function of T_H . In this equation a is the effective radius of the linkage path, α is the thermal diffusivity, r is the radial distance from the sensor to the center of the path, T_A and T_H are the initial ambient and linkage path temperatures, respectively. The good agreement between the two results is obtained because in the numerical calculations property variations and vaporization have competing effects in the determination of the response of an interior point. Specifically, the increase of thermal conductivity with temperature increases heat transfer; whereas vaporization, of course, reduces it.

1. Reverse Combustion Linkage

Therefore, Eq. 1 with α as a function of T_H was used to analyze all the low temperature ($< 200^\circ\text{F}$) responses seen during the Phase 2b linkage. During the period from ignition on Day 94 to Day 114, there were thermal responses of at least 5°F at 17 sensor locations with at least one in each of the eight wells nearest the line between process Wells 5 and 6 (Figure 3). The size, position and temperature parameters for the linkage path were determined using least squares comparisons between temperatures calculated with Eq. 1 and those measured. The comparisons were made in four regions: near Well D and Well O, between Wells F and G and between Wells A and C. The responses in Wells E and B indicate that the linkage path passed directly by these wells. Also, the speed with which it passed between them and the fact that the E-B line coincides with a major fracture direction makes it plausible that the path proceeded along a fissure near these two wells. Therefore, the data from these wells could not be appropriately analyzed with a conduction model.

The early responses shown in Figure 3 along the Well A-C-F-G line indicate the presence of two separate linkage paths. The leveling off seen in the 5-ft response in Well C indicates that the upper path probably did not fully develop. The temperature responses seen in the two levels in Well C and one level in Well A are consistent with a linkage path of equal size and temperature to that passing between Wells F and G, but one that begins to cool rapidly after about Day 106. Day 106 is also approximately the time that the other linkage path proceeded rapidly between Wells E and B which would make this path the preferred flow direction. Figure 4 shows the relative position and size of the linkage paths with respect to the instrumentation wells.

A number of statements concerning reverse combustion linkage can be made as a result of the analysis.

1. Typically, the initial temperature increase shown by the measured data is greater than that predicted. This is consistent with the idea that the initial pulse comes from the active combustion zone whereas the long term response is indicative of the average lower temperatures in the path behind the combustion front.
2. The low thermal conductivity of coal results in large temperature gradients so that small changes in distance result in large temperature changes. Thus, the most accurate interpretations that can be made from the analyses are those relating to position.

FIGURE 3
TEMPERATURE - TIME PROFILES DURING
PHASE 2B LINKAGE

THERMOCOUPLE LOCATIONS REFERENCED
TO BOTTOM OF THE THIRTY-FOOT COAL
SEAM.

Figure 4. Positions of Phase 2b Linkage Paths on Day 115 Based on Analysis of Thermal Data. Paths are Approximately 3 ft in Diameter and Located 5-6 ft Above Coal Seam Floor.

3. Results consistently indicate effective diameters for the linkage path in the range 2.5 to 3.5 ft.
4. The analysis cannot determine accurately the temperature of the path, because temperature has a weak effect on response, and it is also most sensitive to fluctuations in flowrate. Therefore, the responses result from heat sources whose strength may vary widely over the measurement time. Typical temperature values indicated range from 900 to 1300°F.
5. The analysis places the center of the primary linkage path 5 ft from Well D, 3.5 ft from Well O, and 4 ft from Well G. Similarly, the other path is 4 ft from Well D and 4.5 ft from Well C.
6. In all the linkage data there is no evidence of thermal override in the coal seam. The Well A-C path remains about 6 ft from the bottom of the coal seam and the Well F-G path about 5.5 ft from the bottom.
7. None of the low temperature responses are inconsistent with either the analytical model itself or the interpretations resulting from the analysis. However, because of the nature of inverse problems (especially when there are many unknowns), these results do not preclude the possibility of other mechanisms or models accounting for the observed responses.

2. Gasification

When analyzing thermal responses during forward combustion, it is important to recognize that certain regions of the virgin coal can be heated by convective gas flows in addition to possible conduction. In such regions a pure conduction analysis would not be appropriate. A number of factors, however, indicate that the initial temperature increases in Wells H, I, J, K, and N can be considered as primarily due to conduction. All these wells lie 20-30 ft away from the initial high permeability flow paths established during Phase 2b (Phase 3 for Wells N and K) and two dimensional isothermal compressible flow calculations indicate that at such distances there is very little gas flow in the virgin coal. Also, none of the thermocouples show any significant preheating prior to the rapid upturn which has been characterized as due to conduction.

The model chosen to analyze these responses is that of a fixed wall which experiences a step jump in temperature to some typical gasified zone value at the initial time. It is not obvious that such a model is appropriate when the boundary is moving as is the case with the gasified zone boundary. However, numerical calculations indicate that, for boundary velocities greater than 0.25 ft/day, the thermal profile proceeding the boundary is so sharp that the fixed boundary can be used provided the initial time is taken as the time the boundary reached its final position. For slower velocities the model can still be used, however, now the initial time will be some dummy time increment before the final boundary is reached. The inclusion of this time increment in the calculation is necessary in order to account for the preheat zone preceding the slow moving boundary. Two-dimensional calculations show that, due to the insulating properties of the coal, a one-dimensional expression can be used to determine the normal distance from the sensor to the boundary even if the boundary is vertically non-uniform.

Thus, for the one-dimensional case, the appropriate analytical expression is

$$T(x,t) = (T_H - T_A) \operatorname{erfc}(x/2\sqrt{\alpha t}) + T_A \quad (2)$$

where T is the temperature, x is the distance from final gasified boundary, t is the time, α is the thermal diffusivity, and T_H and T_A are the combustion zone and ambient temperature respectively. As before, Eq. 2 provides good agreement with numerical calculations that include property variations and vaporization when α is an empirically determined function of T_H .

The data analyzed using this model included the responses seen late in Phase 2b in Wells H, I, and J (Figure 5) and the response during Phase 3 in Wells K and N (Figure 6). The Well N data extend into cooldown, and therefore the model was modified

Figure 5. Thermal Responses Outside Reaction Zone Boundary at the End of Phase 2b. (Thermocouple Locations (feet) Referenced to Bottom of Coal Seam.)

Figure 6. Typical Measured and Calculated Thermal Responses in Wells Which Remained Outside the Final Reaction Zone Boundary for Phase 3. (Thermocouple Locations (feet) Referenced to Bottom of Coal Seam.)

to include an exponential decay of the boundary temperature beginning when air injection was stopped on Day 213. In general, excellent agreement was obtained between calculated and observed temperatures.

The analysis of the Well H, I and J responses lead to a number of conclusions concerning gasification in the later stages of Phase 2b.

1. The final boundary at the end of Phase 2b (Day 152) for the 10-ft to 20-ft levels was approximately 4-5 ft from Well J and 3-4 ft from Wells H and I.
2. The vertical structure of the final boundary was such that it extended about 1 ft further out from the reaction zone center at the 10 ft level than at the 20 ft level.
3. The predominant reason for the time lag between the responses at higher levels is not the difference in final extent but rather because the upper levels reach the final position later in time. This conclusion implies that the combustion front does not move uniformly across the seam, but rather pivots about the points of furthest extent near the bottom of the seam. This is illustrated more clearly in Figure 7. The actual data used are for levels in the 10 ft to 20 ft region. The 30 ft and 0 ft responses are distorted by conduction in the over

Figure 7. Schematic Diagram of Reaction Zone Boundary Movement Near Well I at the End of Phase 2b. (Section shown is in a plane perpendicular to the Well 5-6 line.)

and underburden respectively. None of the responses outside the 10 to 20 ft range are inconsistent with the extrapolated boundaries indicated by dashed line in the figure.

4. Typical boundary temperatures necessary for good agreement between calculated and measured responses were in the range of 1150°F to 1600°F.

Figure 8 represents an attempt to correlate these analyses with the rest of the thermal data in an attempt to picture the structure of the gasified zone as a function of time. The primary inputs for constructing these contours are the lower level responses in Wells A and Well D and the lack of such in the upper levels, extrapolation of the boundaries and arrival times indicated by analysis of the Well H, I, and J data, and the 20 ft responses in Wells F, G and O. The contours were also constrained to agree with LERC's material balance calculations as to the amount of coal gasified. The contours at the end of Phase 2b are more difficult to draw since the only hard data is the boundary near the H-I-J line and, of course, the need to agree with material balance calculations. Therefore, it was necessary to extrapolate from the upper level responses in Wells A, D and G to draw the contours on Day 152. The effect of the assymetry in the primary linkage path is evident in the shape of the gasified region.

Taken together, Figure 8a and 8b provide a picture of how the UCG process proceeded in the Hanna seam during forward gasification. There is an initial period of rapid horizontal growth at about the level of the linkage path. During this period the vertical growth is slower and is confined to the region near the injection well and adjacent to the linkage path. Then at some point the rate of horizontal extension low in the seam slows, and during the later stages of gasification the boundary "pivots" about the points of furthest extent and moves towards the roof of the coal seam aided by subsidence. Three additional observations support this description of the process. First, if the gasified zone extends very rapidly in the lower third of the seam, then one might expect to see some conduction to upper level thermocouples from below prior to their experiencing high gasification temperatures. Examination of the 15 and 20 ft responses in nearly all the wells shows just that trend. Almost without exception the upturns at these levels are slower than those seen at the 0, 5, and 10 ft levels. Many of the responses are not unlike what would be calculated by conduction from a high temperature boundary 2 to 3 ft away. Second, induced seismic data on Day 132 indicates a region of affected coal 4 to 6 ft beyond Well A at about the 5 ft level. This again indicates much more rapid extension at the lower levels since it is clear from material balance considerations alone that at the upper levels the gasified zone can have nowhere near this extent. Third, passive acoustic source locations in the overburden, which are indications of the zone extending to the roof of the coal seam, are predominantly located to the injection well side of the Well A-C-F-G line. This is consistent with the contours which show greater vertical extent in this region.

Unfortunately, there is insufficient data to accurately draw similar contours for Phases 3. However, analysis of Well N data shown in Figure 6 places the final gasified zone boundary between the 10 and 20 ft levels at a distance of 5 to 6 ft from this well. Once again the final boundary is fairly uniform vertically with the upper levels reaching the final position later. Well K also remained outside the final gasified zone, but these data shown in Figure 6 are more difficult to interpret since the responses are probably due to conduction from boundaries formed by both Phases 2b and 3. The low level of the responses indicate, however, that no high temperature wall could have been closer than 8 ft to Well K.

----- Av. Extent from 0 to 10 ft.

————— Av. Extent from 10 to 30 ft.

Figure 8. Delineation of Affected Coal Regions at 2 Times During Phase 2b. Boundary Locations are Based on Thermal Analyses and LERC Material Balance Calculations.

IV. SEISMIC-ACOUSTIC STUDIES

A. Passive Acoustic Experiment

(L. W. Beckham, 5732)

The analysis of passive acoustic data during Phases 2 and 3 involves determining the following: (a) the frequency distribution of acoustic events, (b) the amplitude distribution of passive signals, and (c) the source locations for active periods during the experiment. Both (b) and (c) require the digitizing of several channels of data for each event selected from the analog playbacks. A total of 170 events from Phase 2b have been selected for examination.

The sources of eleven events on five different days have been determined and are shown in Figure 9. All the locations are in the overburden and are above regions of gasification. The character of the signals suggest the signals result from cracks or sags in the overlying strata associated with roof collapse. As seen in Figure 9, acoustic activity is located only above those regions where gasification has produced high temperatures ($> 300^{\circ}\text{F}$) at the top of the seam. This suggests that the supporting coal has been removed in these regions and roof collapse has begun. This correlation will be further examined with the additional source locations.

Figure 9. Source Locations for Some Discrete Passive Signals. (Number indicates height, in feet, above the coal seam.)

B. Induced Seismic Experiment (L. W. Beckham, 5732)

Induced seismic data obtained during Phase 2b pretest (Day 85), linkage (Day 125), and gasification (Days 132, 139, and 146) periods are being analyzed by two techniques. First, times-of-arrival (TOA) and first peak amplitudes for signals observed pretest and during the test are compared to see if outlines of the process can be delineated by a "shadowing" model. Second, a detailed reflection analysis (given in the Seventh Quarterly Report, page 26) provides additional information on the vertical growth of the reaction.

Examination of the Day 132 data relative to Day 85 has been completed. The study involved comparison of first peak amplitudes and times-of-arrival of twelve detonators signals at each of 33 geophone locations (Well A, B, C, D, F, G). Selected individual comparisons are given in Table III. The time of arrival results indicate that average velocity decreases of 2-4% are evident in regions not directly affected by the process. Larger changes are observed for the process-related attenuation zone (e.g., in geophones C50, C65, and F50). The variations in the amplitude data are generally large and can be attributed to material changes, detonator variations, and the difficulty of automatically picking the maximum amplitude of a single peak. Again definite attenuation can be noted for the lower geophones in Wells C and F. Detailed visual examination of the signals can result in the delineation of the extent of an affected zone as presented in the Seventh Quarterly Report (Figure 11). The S1 to Well B and Well D paths have similarly been examined and the boundary determined.

As another way of summarizing the large number of comparisons, three categories of detonator geophone paths were averaged: (1) high dets to high geophones (paths above the coal seam), (2) low dets to high geophones (path through unaffected portions of the coal seam), and (3) low dets to geophones "behind" the affected zone (paths through affected regions). These averages are given in Table IV.

The slight velocity decrease in unaffected regions is evident and is attributed to removal of water from the natural fracture system of the coal or overburden. Attenuation within the "unaffected" coal seam can also be detected. Large velocity and amplitude decreases are definitely observed when paths intersect the process. Generally, however, the standard deviation of these averages are on the order of 50-70% of the average. Thus, while definite effects are noted, these results imply that statistical analysis of the data is necessary, and that individual comparisons may be extremely variable.

Table III

Selected Time of Arrival and Amplitude Data for the Induced Seismic Experiment[†]

			Detonator (location above floor of 30 ft coal seam)											
			1	2	3	4	5	6	7	8	9	10	11	12
			-40	-30	-20	-10	0	7.5	15	22.5	30	40	50	60
Geophone (location above floor of 30 ft coal seam)	A20	60	* 1.05	3 *	-2 0.90	-1 *	-5 0.94	-1 0.87	-5 *	-3 0.30	0 0.61	0 0.82	-3 1.03	* 0.55
	C40	40	-4 0.50	-5 0.46	-4 0.50	-1 0.59	-7 0.75	-5 0.71	-3 0.62	-2 0.61	-2 0.61	* 0.44	-2 1.51	-4 0.97
	C50	30	-7 0.46	-9 0.41	-10 *	-8 0.58	-13 0.86	-3 0.19	-4 0.32	-8 1.63	0 0.92	* 1.30	-4 1.75	-5 2.26
	C65 ¹	15	-31 *	-41 *	-44 *	-31 0.17	-35 0.19	-36 0.23	-41 1.08	-23 0.65	-14 0.84	* 0.06	-14 0.69	-8 0.53
	D40	40	-3 0.95	-3 0.94	-3 0.90	-4 1.11	-4 1.08	-6 0.94	-7 0.83	-2 0.86	0 1.41	0 *	-2 1.55	0 1.00
	D65	15	-12 0.62	-13 0.55	-11 0.55	-16 0.78	-16 1.50	-7 1.34	* 6.35	0 2.06	-4 1.05	-3 1.56	-4 1.80	-4 2.05
	F30	50	-6 0.46	-4 *	-4 *	-4 *	-4 0.63	-4 0.68	-4 0.56	-3 0.55	0 0.69	* 0.64	-4 0.81	* *
	F40	40	-1 0.27	-7 2.63	-7 0.25	-4 0.38	-6 0.45	-5 0.58	-4 4.57	-3 0.56	-2 0.63	* 0.84	-4 0.47	-3 0.25
	F50	30	-6 0.33	-22 0.58	-39 *	-33 *	-10 0.05	-3 0.21	* 1.23	-6 0.38	* 1.47	-3 1.17	-7 1.57	-8 1.10
	G50	30	-16 0.28	-38 *	-45 0.09	-32 0.16	-10 *	1 0.20	5 0.41	* 0.35	-3 0.70	-2 0.84	-1 0.73	-1 0.39

*Improper signal detection by the reduction code.

[†]Upper value: Percentage change in time-of-arrival; Day 132 relative to Day 85.

Lower value: First peak amplitude: Day 132/Day 85 with both days normalized to a given geophone to account for day-to-day detonator variations.

¹ Temperature at this location was approximately 200°F.

Table IV

Averaged Changes in Times-of-Arrival and Amplitude
Between Day 85 (Pretest) and Day 132

	Δ Velocity	Δ Amplitude*	Number Averaged
Group 1 Paths above the coal Seam	-3.0%	1.05	76
Group 2 Paths through unaffected regions of the coal seam	-3.8%	0.73	44
Group 3 Paths through affected regions of the coal seam	-14.4%	0.46	28

*First peak amplitude (Day 132/Day 85)

During the week of November 15, 1976 a surface-to-downhole induced seismic experiment was carried out at the Hanna Site. Its purpose was to evaluate whether such a technique utilizing Vibroseis signal source and processing techniques could be used to evaluate the extent of the posttest gasification zone. The data were collected by a van-mounted minicomputer which digitized the Vibroseis reference signal and the signal received by a hydrophone below the coal seam in Well S1. The minicomputer controlled the initiation and six second sweep of the Vibroseis unit. Vibroseis parameters were also varied to determine if an optimum frequency band or sweep method existed. Data were taken on both sides of Well S1 so as to obtain "background" and posttest comparisons. The data are being analyzed.

During this test, the insulation on the hydrophone cable was burned at a depth of 285 ft, approximately midseam in this well. This result indicates that a breach in S1 had occurred at this depth and that increased temperatures from Phase 2b extended to Well S1, forty feet from the Well 5-6 line.

V. ELECTRICAL STUDIES

A. Results from the Electrical Measurements (L. C. Bartel, 5732 and R. W. Seavey, 5733)

During Phases 2 and 3, there were two types of electrical measurements made:

(1) a modified Schlumberger (MS) technique, where the current electrodes are located either side of the experiment area and separated by approximately five times the depth of the coal seam, and (2) a direct excitation electrical potential (DEEP) technique where one current electrode is the production well and the other current electrode is an outlying well. Both the MS and DEEP methods utilize the same fixed potential probe arrays on the surface and in the instrumentation wells. In the MS configuration the applied current lines are roughly parallel in the coal seam and are distorted by regions of hot conductive coal. In the DEEP configuration the hot conductive coal in contact with the production well forms part of the current electrode and the geometry of the current source varies with the shape of the reaction zone. The results from the MS and DEEP techniques are best expressed in terms of resistivity and as potentials, respectively.

In addition to the DEEP surface equipotential contour plots reported in the Seventh Quarterly Report, a complete set of the DEEP technique potential data for Phase 2b has been reduced and contour plots made. From these data an equipotential contour plot movie has been made which graphically shows the changes produced in the equipotential contours during the linkage and gasification. The motion of the reaction zone is clearly evident and is consistent with the thermal data and "picture" which is available. The movie also illustrates the quality of the experimental data; only continuous changes were observed for the every four hour, and sometimes hourly, scans that were made.

The DEEP technique potential data, along with the movie depicting the changes, demonstrate the feasibility of using the DEEP technique to map the progression of the hot conductive coal during the underground gasification process. However, in order to quantify the areal extent of the reaction zone, a detailed comparison to model calculations is needed. Work on the model calculation is in progress as reported in Section V-B of this report.

Preliminary results from the downhole potential probes for the DEEP technique are encouraging. An equipotential contour plot of the downhole potential data from the DEEP technique for Day 117 is shown in Figure 10. For this figure the measuring points are the mid-seam probes fielded in the instrumentation wells as shown in the figure, thus limiting the number of points contributing to the plot. A potential ridge is evident from Well 5 to Well 6 and in the vicinity of Wells B, E, F, O, and G. As equipotential lines are perpendicular to lines of current, this ridge represents a region of

increased current, Thus, the contour plot shows that on Day 117 the location of the hot coal is along a line which is in agreement with the location of the linkage path from the thermal data and the surface equipotential contour plots discussed in the Seventh Quarterly Report.

There were some recording problems for the Phase 3 electrical data which requires extra data reduction effort. Preliminary results suggest an early period where the hot coal was still in contact with current electrode (Well 5). This is followed by an apparent loss of contact sometime between Day 173 and Day 185. (In this period, no data were obtained due to an equipment failure.) On Day 182, Well 8 became the production well for the balance of Phase 3. Thus, for the gasification between Wells 7 and 8, the reaction zone is not in contact with a current drive well (Well 5), and a different current electrode configuration can be evaluated.

Figure 10. Equipotential Contours Measured by Mid-Seam Electrical Probes in Each of the Instrumentation Wells on Day 117 (Phase 2b).

B. Model Calculations of Electrical Data (L. C. Bartel, 5732)

Two analytical approaches are proposed to relate the reaction zone size and location to the DEEP data: a downward continuation of the potential method and a least squares fitting of model calculation parameters. These two methods are discussed here.

One downward continuation method utilizes a Taylor's series expansion of the potential in the downward direction where the measured surface potentials are used to evaluate the derivatives. For example, the potential ϕ at a depth h is given by

$$\phi(x,y,h) = \phi(x,y,0) + \left. \frac{\partial \phi}{\partial z} \right|_{z=0} h + \frac{1}{2} \left. \frac{\partial^2 \phi}{\partial z^2} \right|_{z=0} h^2 + \dots$$

where at the surface $\partial \phi / \partial z = 0$ and ϕ satisfies Laplace's equation such that

$$\frac{\partial^2 \phi}{\partial z^2} = - \left(\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} \right)$$

Using a finite difference technique, the experimental data are used to evaluate $\partial^2 \phi / \partial x^2$ and $\partial^2 \phi / \partial y^2$. Thus

$$\left. \frac{\partial^2 \phi}{\partial x^2} \right|_{z=0} \rightarrow \frac{\phi(x+\Delta x, y, 0) + \phi(x-\Delta x, y, 0) - 2\phi(x, y, 0)}{(\Delta x)^2},$$

$$\left. \frac{\partial^2 \phi}{\partial y^2} \right|_{z=0} \rightarrow \frac{\phi(x, y+\Delta y, 0) + \phi(x, y-\Delta y, 0) - 2\phi(x, y, 0)}{(\Delta y)^2},$$

where in the partial derivatives and in the expansion the $\phi(x,y,0)$'s are the experimental data at the x, y positions.

This downward continuation technique has been applied to a set of calculated DEEP potentials. Preliminary results indicate that the resolution of the length of the current source using this downward continuation method does not appear to be very satisfactory.

Model calculations for the DEEP method can be used to determine the size and location of the hot conducting coal. In this proposed method, parameters representing the size and shape of the reaction zone are to be adjusted to give the best fit to the data. A function of these m parameters, say $\alpha_1, \alpha_2, \dots, \alpha_m$, is defined as

$$f(\alpha_1, \dots, \alpha_m) = \sum_n |\phi_{\text{meas}}(\vec{x}_n) - \phi_{\text{calc}}(\alpha_1, \dots, \alpha_m; \vec{x}_n)|^2,$$

where the $\phi_{\text{meas}}(\vec{x}_n)$'s are the measured potential data at the positions $\vec{x}_n$ and the $\phi_{\text{calc}}(\alpha_1, \dots, \alpha_m; \vec{x}_n)$'s are the calculated potentials. The summation is over all the measuring positions. The function $f(\alpha_1, \dots, \alpha_m)$ is minimized by adjusting the α_i parameters. The parameters representing the size of the reaction zone are constrained by the volume of coal consumed which can be determined from mass balance calculations. Preliminary results from the calculation of the DEEP technique potentials show that by adjusting the parameters equipotential contours similar to the data discussed in the Seventh Quarterly Report can be obtained. Work is continuing on this fitting procedure.

VI. DATA SYSTEMS DEVELOPMENT

A. Field Data Acquisition and Recording System (K. M. Kimball)

Available analog instrumentation, recording systems, and field trailers were used to acquire data from many of the instrumentation techniques which were fielded in conjunction with the Hanna II in situ coal gasification experiment. The resistivity, acoustic and seismic techniques were particularly analog intensive and required time-consuming playback, digitizing and handling procedures in Sandia's Data Reduction Facility before data analysis and interpretation was possible. The need for a field digital data acquisition system was recognized early in the program and several studies have been conducted during that time. These have culminated in the definition of a minicomputer-based data acquisition and recording system to be fielded in conjunction with the Hanna IV test.

The system will provide the following capabilities:

- (1) On-site access to all data acquired during the test for evaluation of experiment status and progress.

- (2) On-site production of digital data tapes compatible with the large scientific Sandia computers where subsequent, more complex processing and analyses can be performed. This eliminates the need for intermediate playback and digitizing activities which are time consuming and manpower intensive and which have produced large delays between data acquisition and analyses.
- (3) Continuous monitoring experiments of several month duration and through the use of data compression, selective recording and partial reduction, store only significant information. For example, an average reading instead of n individual readings, the time-of-arrival of a seismic signal and not the entire analog or digital signal, only temperature changes from a constant observed level, etc. need to be retained.

Specific capabilities depend upon the requirements of the individual instrumentation techniques to be fielded. Different input subsystems have been designed for the thermal, electrical, and acoustic/seismic measurements.

The design of the field system has been completed. Approval for the automatic data processing (ADP) equipment has been obtained and a purchase order has been established; other equipment for the system has either been received or is on order. The system will be housed in an instrument trailer which has been redesigned and is being modified. Software development activities have been initiated and a similar minicomputer is available at Sandia for this work. Personnel to be associated with the system attended an introductory course provided by the ADP supplier.

Basically the system consists of: (a) central processing unit with 64K words of memory, (b) digital input/output interface for the thermocouple subsystem, time-base decoder, and control for the electrical subsystem, (c) a wide range analog input subsystem for the 64 channel electrical subsystem and 16 channels of low level seismic data, (d) peripheral control interface for the analog subsystem and acoustic subsystem, and (e) a set of peripherals including a dual cartridge disc, two nine-track tape drives, terminal console, CRT graphics terminal and a printer/plotter with hard copy unit. The entire system is expandable and can be readily modified for other requirements in future tests.

The acoustic subsystem is the Universal Multi-Channel Signal Processor (UMSCP) first described in the Fifth Quarterly Report, Section VI-C. This LSI microprocessor-based system is designed to digitize and preprocess moderate and high rate data and will be used for the passive acoustic experiment on Hanna IV. Assembly is underway and interfacing with different terminals and with the ADP system have been designed. Initial tests of this subsystem with Hanna II acoustic tapes will be conducted next quarter.

V. PUBLICATIONS, PRESENTATIONS, AND BRIEFINGS

A. Publications

1. S. G. Beard and R. P. Reed, "Some Observations from Temperature Measurements on Recent Underground Coal Gasification Experiments," Sandia Laboratories Report, SAND76-0418, August, 1976.
2. D. A. Northrop, Editor, "Instrumentation and Process Control Development for In Situ Coal Gasification: Seventh Quarterly Report - June through August 1976," Sandia Laboratories Report, SAND76-0612, October 1976.
3. L. W. Beckham, "Adaptive Processing of Seismic Signals in Noise for Improved Time of Arrival and Amplitude Estimates," Sandia Laboratories Report, SAND76-0553, September, 1976.

B. Presentations

1. L. C. Bartel, S. G. Beard, L. W. Beckham, R. P. Reed, and R. W. Seavey, "Instrumentation Results from an In Situ Coal Gasification Experiment," Presented by L. C. Bartel at the 51st Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, held in New Orleans, October 3-6, 1976. This presentation was published as SPE paper 6151.
2. L. W. Beckham and T. M. Schultheis, "Field Sensing and Processing of Acoustical Data for In Situ Coal Gasification," Presented by T. M. Schultheis at the 1976 CUBE Symposium, Albuquerque, NM on October 26-27, 1976.

C. Briefings

1. David A. Northrop, briefing on results from Hanna II and presentation of the thermal data movie for Dr. Phillip C. White, Assistant Administrator for Fossil Energy/ERDA on October 27, 1976 in Washington, D. C. This briefing was repeated twice on the same date for the staffs of the Fossil Energy Subcommittee of the House Science and Technology Committee and the Senate Interior Authorization Committee.
2. David A. Northrop, briefing on Sandia's in situ instrumentation development and fossil energy programs for members of the American Industrial Development Council and New Mexico Industrial Development Executives Association on October 22, 1976 in Albuquerque, NM.

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