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INSTRUMENTATION FOR IN SITU COAL GASIFICATION:
AN ASSESSMENT OF TECHNIQUES EVALUATED ON THE
HANNA II EXPERIMENT

D. A. NORTHROP, S. G. BEARD, L. C. BARTEL,
L. W. BECKHAM AND P. J. HOMMERT

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by

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ABSTRACT

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The Hanna II in situ coal gasification experiment was conducted by the Laramie Energy Research Center during 1975-76. As part of this experiment, Sandia Laboratories designed, fielded, and evaluated seven instrumentation techniques and several variations of them. These belonged to two general classes: (a) diagnostic techniques (thermal, in-seam gas sampling and pressure, and overburden tilt and displacement) to obtain data for process characterization and (b) remote monitoring techniques (electrical, passive acoustic, and induced seismic) which are being developed to provide a continuous, real-time map of the in situ process which would be used in a process control system. Assessments of these techniques have been made with respect to their feasibility, information obtainable, and future development and applications; in general, very positive assessments were obtained.

Extensive thermocouple arrays, which incorporated special branched circuitry for data validation, provided the most detailed characterization of in situ coal gasification yet obtained. The feasibility of in-seam gas sampling and pressure measurements was demonstrated and composition changes due to the advancing reaction front were detailed. The thermocouple circuits and gas sampling and pressure canisters are part of a diagnostic well specification now under development for general in situ applications.

Promising results were obtained for the remote monitoring techniques. Two different electrical configurations were employed: direct excitation electrical potential (DEEP) and a modified Schlumberger (MS) technique. Contour maps of potential data from a surface array showed the location and movement of the reaction at 300 ft depth. Mapping the source of process-related acoustic signals was shown to be feasible. These signals originate in the overburden and are related to areas of extensive gasification and coal removal. Borehole-to-borehole induced seismic techniques were able to delineate the advance of the gasification process.

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EXECUTIVE SUMMARY

Seven instrumentation techniques and several variations of them have been fielded and evaluated on the Hanna II in situ coal gasification experiment conducted in 1975-76. Two different classes of instrumentation are under development: (a) methods to obtain diagnostic information to characterize the gasification process and contribute to its understanding, and (b) remote monitoring methods which will provide a picture or map of the dynamic process to be used as part of an overall process control system. Assessment of these instrumentation techniques as applied to in situ coal gasification and based upon two years of field experience is the objective of this report.

Temperature: The hardware, fielding, data acquisition, data validation, and data analysis aspects of in situ thermal measurements have been investigated. Conventional and branched thermocouple circuits reliably measured thermal responses during pre-ignition air injection (48-55°F), reverse combustion linkage (~ 200°F), and rapid increases to 1000-1900°F during passage of the gasification front. Most sensors failed after time at 1300-1900°F and evidence for mechanical failure at lower temperatures due to subsidence was also obtained. Emphasis was placed upon the validation of thermal data by utilizing circuit resistance data and the noise emfs and redundant temperatures available from branched thermocouple circuitry in order to avoid misinterpretation because invalid segments of data frequently appeared to be plausible. Development directions resulting from these results include: (1) a methodology for selecting well locations to increase the amount of information obtained from a given number of wells of limited thermal radius (7-10 ft conduction response), (2) a modular in situ thermocouple assembly to simplify procurement and reduce costs and fabrication time, and (3) a minicomputer-controlled data acquisition system to permit convenient temperature and circuit diagnostic measurements for real-time data validation and display.

Analyses of the thermal data have resulted in the best characterization of in situ coal gasification yet obtained. These analyses have: (1) determined the size (2.5 - 3.5 ft), temperature (900 - 1300°F) and position ($\pm 1/2$ ft) of the reverse combustion linkage path, (2) confirmed the lack of thermal or bouyant override, (3) indicated the presence of a second, partially-developed linkage path, (4) characterized boundary motion during forward gasification in that there was an initial expansion near the bottom of the coal seam and that the vertical profile was not constant, (5) determined final boundary location from responses of sensors outside the boundary, (6) characterized the combustion front profile as being narrow (~ 2 ft), with high heating rates (5-9°F/min), and without an extensive pyrolysis zone, (7) measured collapse and fracturing at least 30 ft into the overburden, and (8) improved mapping of the process as a function of time by combining field thermal data and process model predictions. In addition, a movie of the thermal data graphically depicts combustion linkage near the bottom of the coal seam and the upward and outward advanced of the gasification process throughout the coal seam.

In-Seam Gas Sampling and Pressure: Long-line gas sampling techniques have been shown to be feasible in obtaining in-seam gas concentrations and pressure data for diagnostic characterization of the in situ process. Pressure data were particularly useful during reverse combustion. Composition data can be used to determine flow paths remote from the reaction zone and to measure relative differences and ratios between H_2 , CH_4 , CO , CO_2 , and O_2 which reflect compositional changes due to the shift, reduction, and other reactions. The hydrology of the Hanna site was favorable for this technique; operation under higher hydrostatic pressure at greater depths or with greater water influx will have to be assessed. Improved design features (reduced size, positive sealing, continuous tubing, etc.) have been incorporated into units for future field testing. This gas sampling system will be combined with the modular in situ thermocouple system in a specification for a "diagnostic well" for in situ thermal processes.

Tilt and Displacement: Tilt meters and displacement gauges were fielded in selected instrumentation wells to obtain diagnostic information on the response of the first 50 ft of overburden above the coal seam. These techniques, as fielded, did not detect the degree of roof collapse suggested from other indirect evidence. Failure of the techniques is attributed to: (1) the large number of cables and other instrumentation fielded in the same well resulting in a reinforced grout column and (2) the uncertain sensor-grout-formation interfaces. Future subsidence instrumentation activities will focus upon the displacement measurement via a modified slifer or time domain reflectometry technique fielded in a well dedicated to this measurement.

Electrical: The basis for these techniques is that hot ($> 650^\circ C$) carbonized coal is conductive ($< 1 \Omega\text{-m}$ resistivity) and thus large changes in resistivity occur during the drying ($> 10^8 \Omega\text{-m}$) and gasification of a virgin, water-saturated coal seam ($\sim 200 \Omega\text{-m}$). Two electrical methods are under development: a modified Schlumberger (MS) technique which is a galvanic resistivity method, and a direct excitation electrical potential (DEEP) technique which is essentially a dynamic "misse-a-la-masse" method. In the MS configuration, the applied current lines 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 and extent of the reaction zone. The potential changes produced in either method are measured by a fixed surface probe array and can be presented as a two-dimensional contour map. Both techniques can utilize the same surface probe array, current drive system, data acquisition and reduction methods and, thus, are easily fielded together. Results from Hanna II indicate that: (1) the location and symmetry of the linkage path can be detected using the MS technique when a component of the applied current lies in the linkage direction, (2) the DEEP technique can give an excellent, qualitative remote picture of the symmetry, motion, and extent of the reaction zone, and (3) model calculations of both techniques are in agreement with the field data and are necessary for their interpretation. Further work is required to solve the inverse

analytical problem: quantitative description of the reaction zone from an observed potential distribution. The feasibility of these electrical techniques for remotely monitoring the reaction zone in in situ coal gasification has been established.

Passive Acoustic: Three types of passive acoustic signals related to the gasification process have been identified. The times-of-arrival of discrete signals have been used to determine the spatial origins of the activity by using a simple linear least-squares technique. These acoustic events were located in the overburden above the burning coal seam and their intensity as well as frequency of occurrence are related to the degree and extent of gasification. Process motion is suggested by the origins of these subsidence noises and these acoustic events may be used as a measure of subsidence over a region that has been gasified. The boundaries of the process are essentially delineated by the extent of the activity as indicated by correlations with thermal burn front contours. Feasibility of the technique has been demonstrated. Future development focuses upon an instrumentation system to detect, process and locate these events during real-time monitoring of the in situ coal gasification process.

Induced Seismic: The basic philosophy behind the induced seismic instrumentation technique is that changes in the elastic parameters of the media brought about by the gasification process are observable in terms of changes in seismic signal parameters such as time-of-arrival (velocity) and amplitude. The seismic measurements made during the experiment indicate that a borehole-to-borehole technique based on transmission-timing and reflection-timing models can be used to characterize the area affected by gasification. Changes in the times-of-arrival along specific ray paths provide the spatial correlation to the process in both the transmission and reflection analyses. Reflection and transmission studies during different stages of the experiment indicate that the linkage phase is not detectable but that the extent and motion of the gasification process boundaries can be found by carefully monitoring signal parameters along known ray paths. Diffraction modeling has been done and diffraction effects are significant. These and attenuation of higher frequencies appear to limit the extension of the technique for borehole-to-surface (or vice versa) or surface-to-surface remote monitoring applications.

INTRODUCTION

Successful development of in situ coal gasification will require both (a) a thorough understanding of the chemical and physical mechanisms of the in situ reaction 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 lack of technical understanding and process control have been factors which have prevented the widespread development of in situ coal gasification despite worldwide interest and investigation over many years. Sandia Laboratories' program for instrumentation and process control development addresses these factors.

Two broad classes of instrumentation are needed to satisfy these factors. In the first class are diagnostic techniques where sensors are emplaced within the experimental area to give direct information on the process: temperatures, pressures, gas compositions, and a direct measure of the extent and configuration of the process as a function of time. The objective for these techniques is process characterization and understanding -- the prerequisite for process control. In the second class are remote monitoring techniques where sensors are economically placed in surface arrays or in a few wells with widespread coverage and which will provide a real time map or picture of the process. Control of an in situ gasification process on a commercial scale will be analogous to that for a surface plant with one large exception: the reactor size and configuration varies as a function of time. These techniques will provide this additional information necessary for process control.

Sandia Laboratories has been associated with the Laramie Energy Research Center's (LERC) in situ coal gasification program and its field experiments being conducted near Hanna, Wyoming. Preliminary instrumentation efforts on the Hanna I experiment during 1973-74 demonstrated that process-related effects could be detected by electrical, acoustic, and thermal techniques.⁽¹⁾ Based upon these results a comprehensive instrumentation effort was designed as an integral part of the Hanna II experiment conducted in 1975-76. Impressive gas production and resource utilization results were obtained from this test.⁽²⁾ In addition, it was the most thoroughly instrumented in situ experiment ever conducted and, as a result, provided the best picture yet obtained of an in situ coal gasification process.

This report presents a description, results, and evaluation of the instrumentation techniques fielded by Sandia on the Hanna II experiment. The emphasis has been placed upon providing an assessment of the individual techniques based upon actual field experience. This assessment includes examples of the information which can be obtained and directions for future development. Comprehensive, detailed presentation of all data and results are not given and such information will appear in additional papers for the individual techniques. A complete listing of program-related reports and publications is given in the Program Bibliography.

The Hanna II Experiment

The linked vertical well concept is being pursued by LERC in their in situ coal gasification program.⁽³⁾ This process uses reverse combustion, in which the reaction front advances against the flow of air, to create a permeable path or link between vertical wells emplaced to the coal seam. The link is a localized channel of carbonized coal with a high permeability which allows high air injection rates at relatively low pressures. Once linkage between wells is accomplished, the much higher injection rates cause the reaction front to move with the flow, and, in this forward combustion mode, gasification occurs and the entire coal seam between the wells and to a significant extent to either side is gasified and the product gases recovered.

The Hanna II in situ coal gasification experiment was conducted in two intervals. Phase 1, a site characterization and preliminary gasification test, was fielded and conducted between January and August, 1975.⁽⁴⁾ Based on the Phase 1 results, the plans for the major parts of the experiment were finalized and Phases 2 and 3 were fielded 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 description of all aspects and results of the experiment are given in papers prepared by LERC.⁽²⁾ A schematic description of all phases is given in Figure 1. Dated activity summaries for all phases are given in Table I for reference in this report.

Instrumentation and Fielding Summary

Seven different instrumentation techniques were evaluated during Hanna II. In addition, different configurations (e.g., current electrode and source), locations (e.g., surface or downhole), and sensors (e.g., materials, type, etc.) were evaluated, effectively increasing the scope of the instrumentation effort. The techniques fielded and evaluated on the different phases are given in Table II.

Four instrumentation wells and a limited surface electrical probe array were fielded on Phase 1. Geophones, resistivity probes, thermocouples, and a gas sampling canister were the sensors emplaced in the wells. A twenty-three probe surface array on 10 ft spacing and two current injection wells located 750 ft away from the array formed the configuration for the electrical resistivity measurements. The Phase 1 well and instrumentation layout is given in Figure 2; downhole sensor locations are listed in Table III. Instrumentation fielding occurred during February; the additional effort required for fielding during the Wyoming winter should be considered in future planning.

PHASE 1, 1975

- (a) DETERMINE MAJOR PERMEABILITY DIRECTIONS
- (b) LINK AND GASIFY (Phase 1a)
- (c) LINK AND GASIFY (Phase 1b)

PHASES 2 and 3, 1976

- (a) LINK AND QUENCH (Phase 2a)
- (b) LINK AND GASIFY (Phase 2b)
- (c) LINE LINK ATTEMPTED (Phase 3)
- (d) TWO WELL GASIFICATION ADOPTED (Phase 3)

Fig. 1 - The Hanna II In Situ Coal Gasification Experiment.

Fifteen instrumentation wells, two shot wells, and surface geophone and electrical probe arrays were fielded for Phases 2 and 3 as shown in Figures 3 and 4. Geophones, resistivity probes, different thermocouple circuits, gas sampling canisters, pressure transducers, tilt meters, and displacement gauges were the sensors emplaced in the instrumentation wells; a complete summary of the downhole sensor locations are given in Table IV. Two fiberglass-cement cased wells, S1 and S2, were used for the detonator strings employed in the induced seismic measurements. A fifteen geophone surface array was emplaced at approximately 20 ft depth to evaluate the downhole-to-surface induce seismic configuration. Seventy-six probes at 5 ft depth and on 10 ft spacing arrayed over the experimental area, four outlying reference probes, and two outlying current injection wells were used for the electrical measurements.

Downhole instrumentation was fielded in uncased, grout-filled wells by the following procedure. The wells were drilled with a 7-7/8 in. bit with air circulation and with care being taken to ensure straightness and verticality for accurate sensor location. The floor of the coal seam in each well was used as the reference location for the instrumentation string. All installation was performed in an enclosed flat-bed trailer positioned over the well which offered protection from the weather and facilities for handling the sensors and cable spools. The different sensors were fastened along with a measuring tape to a messenger cable which was lowered by a winch into the hole. The hole

TABLE I
Dated Activity Summary of the Hanna II In Situ Coal Gasification Experiment

PHASE 1

<u>Day (1975)</u>	<u>Date (1975)</u>	<u>Activity</u>
97	April 7	Directional air flow tests; injection in Well 1 with production at Wells 2, 3 and 4.
107	April 17	Begin pneumatic linking test; air injection in Well 1 with production at Well 3.
141	May 21	Begin ignition in Well 1; Phase 1a initiated.
145	May 25	Remove heater; air injection switched to Well 3 with production at Well 1.
155	June 4	Reverse combustion linkage, Phase 1a.
155-192	June 4-July 11	Gasification. ~ 1200-1500 cfm injection at Well 3; ~ 1800 cfm production at Well 1.
192	July 11	Air injection switched to Well 2 with production remaining at Well 1; end Phase 1a and initiate Phase 1b.
203	July 22	Reverse combustion linkage, Phase 1b.
203-240	July 22- August 28	Gasification. 300-1100 cfm (intentionally varied) injection at Well 2; 500 to 2200 cfm production at Well 1.
240	August 28	Air injection halted; terminate Phase 1b.

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.

TABLE I (Continued)

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.

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.

TABLE II
Instrumentation Techniques Under Development and
Evaluated on the Hanna II In Situ Coal Gasification Experiment

	PHASE 1	PHASE 2	PHASE 3
<u>Diagnostic</u>			
Temperature (Branched Circuitry)	X	X	X
In-Seam Gas Sampling and Pressure	X	X	X
Subsidence: Tilt and Displacement		X	X
<u>Remote Monitoring</u>			
Direct Excitation Electrical Potential		X	X
Modified Schlumberger (Resistivity)	X	X	X
Passive Acoustic	X	X	X
Induced Seismic		X

Fig. 2 - Instrumentation and Well Layout for Phase 1 of the Hanna II Experiment (March 1975).

TABLE III
Instrument Locations, Hanna II, Phase 1

		WELL AA	WELL BB	WELL CC	WELL DD
Installation Date		2/22/75	2/19/75	2/17/75	2/21/75
Well Collar to Reference*		305.2 ft	304.7 ft	303.0 ft	300.8 ft
Geophones	a	57.0	223.0	57.0	57.0
	b	40.0	140.0	40.0	40.0
	c	21.0	57.0	21.0	21.0
	d	6.0	40.0	6.0	6.0
	e	-5.0	21.0	-1.0	-1.0
	f	-	6.0	-	-
	g	-	-5.0	-	-
Resistivity Probes	a	32.0	32.0	32.0	32.0
	b	13.0	13.0	13.0	13.0
	c	-1.0	-1.0	-1.0	-1.0
Thermocouples	a	79.8	80.1	79.0	80.3
	b	44.9	45.0	44.9	44.9
	c	34.9	35.0	34.9	35.0
	d	30.0	30.0	30.0	30.0
	e	24.9	27.5	25.0	25.1
	f	20.0	25.0	20.0	20.1
	g	15.0	22.4	15.0	15.0
	h	-	20.2	5.0	-
	i	-	18.0	-	-
	j	-	15.0	-	-
	k	-	5.0	-	-
Gas Sampling Canister		-	17.5	-	-

* All instrument locations are referenced to the bottom of the coal seam in each well. Positive numbers are above reference; negative numbers are below reference.

Fig. 3 - Well Locations for Phases 2 and 3 of the Hanna II Experiment (Nov. 1975)

Fig. 4 - Instrumentation and Well Layout for Phases 2 and 3 of the Hanna II Experiment (November 1975).

TABLE IV - DOWNHOLE INSTRUMENTATION LOCATIONS; PHASES 2 and 3

		WELL A	WELL B	WELL C	WELL D	WELL E	WELL F	WELL O	WELL G
Installation Date		10/18/75	10/15/75	10/8/75	9/20/75	10/20/75	10/17/75	10/10/75	10/16/75
Well Collar to Reference ⁽¹⁾		299.3 ft	297.1 ft	299.2 ft	301.7 ft	298.1 ft	299.7 ft	300.6 ft	299.2 ft
Geophones	a	60.0	60.0	60.0	60.0	60.0	60.0	60.0	120.0 ⁽⁵⁾
	b	50.0	50.0	50.0	50.0	50.0	50.0	50.0	105.0
	c	40.0 ⁽²⁾	40.0	40.0	40.0	40.0	40.0 ⁽²⁾	40.0	90.0
	d	30.0	30.0	30.0	30.0	30.0	30.0	30.0	75.0
	e	22.5	22.5	22.5	22.5	22.5	22.5	22.5	60.0
	f	15.0	15.0	15.0	15.0	15.0	15.0	15.0	45.0
	g	7.5	7.5	7.5	7.5	7.5	7.5	7.5	30.0
	h	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0
	i	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	0.0
	j	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0
Resistivity Probes	a	32.0	31.7	32.0	32.1	32.1 ⁽⁴⁾	32.0 ⁽⁴⁾	32.0	32.0
	b	16.0	16.0	16.0	16.0	16.3 ⁽⁴⁾	16.1 ⁽⁴⁾	16.0	16.5
	c	-2.0	-3.0	-2.0	-2.0	-2.0 ⁽⁴⁾	-2.0 ⁽⁴⁾	-2.0	-2.0
Thermocouple Levels (Low Temp)	a	74.3	69.3	35.2	64.1	35.0	35.5	52.9	35.3
	b	49.0	35.1	32.7	30.2	30.3	30.3	35.2	30.6
	c	30.2	32.5	30.2	30.0	25.0	30.2	30.0	30.4
	d	30.0	30.0	25.1	20.2	20.2	25.2	25.0	25.3
	e	25.2	27.7	20.1 ⁽³⁾	15.1	20.1	20.2 ⁽³⁾	20.0	20.2
	f	22.5	22.6	14.9	12.7	15.0	15.5	14.9	15.6
	g	20.1	17.9	10.5	10.1	10.0	10.1	10.3	10.4
	h	17.6	15.2	5.0	7.7	5.1	5.1	5.0	5.3
	i	15.1	12.5	-0.1	5.2	0.0	0.0	0.0	0.0
	j	12.5	5.2	-	2.8	-	-	-	-
	k	10.0	0.2	-	0.2	-	-	-	-
	l	0.0	-2.4	-	-10.0	-	-	-	-
Thermocouple Levels (High Temp)	a	-	65.0	65.0	-	65.0	65.0	-	-
	b	-	20.0 ⁽³⁾	15.0 ⁽³⁾	-	20.0 ⁽³⁾	20.2 ⁽³⁾	-	-
	c	-	15.0	-	-	15.0 ⁽³⁾	16.0	-	-
	d	-	-	-	-	-	15.0	-	-
Gas Sampling Canister		-	19.0	19.0	19.0	19.0	19.0	19.0	19.0
Pressure Transducer		-	-	19.5	-	-	19.5	-	19.5
Tilt Meters	a	-	67.2	71.0	-	-	71.0	-	-
	b	-	55.0	55.0	-	-	55.0	-	-
Displacement Gauge	reference	-	-	107.3	-	104.9	-	-	104.9
	a	-	-	83.9	-	83.6	-	-	83.6
	b	-	-	62.5	-	62.4	-	-	62.3
	c	-	-	50.0	-	50.1	-	-	50.1
	d	-	-	35.0	-	35.0	-	-	35.0

NOTES: (1) Locations are referenced to the bottom of the coal seam in each well. Positive and negative numbers are distances in feet above and below the reference, respectively.

(2) 10x downhole amplifier fielded.

(3) Two thermocouples at this level.

(4) High temperature resistivity probes and cables.

(5) 100x downhole amplifier fielded.

TAB E IV (Continued)

		WELL H	WELL I	WELL J	WELL K	WELL L	WELL M	WELL N	WELL S1
Installation Date		9/18/75	9/16/75	9/11/75	9/6/75	9/4/75	9/3/75	8/30/75	8/29/75
Well Collar to Reference ⁽¹⁾		295.6 ft	297.8 ft	300.5 ft	302.4 ft	297.3 ft	300.7 ft	298.7 ft	300.0 ft
Geophones	a	60.0	60.0	60.0	60.0	60.0	60.0	60.0	-
	b	50.0	50.0	50.0	50.0	50.0	50.0	50.0	-
	c	40.0	40.0	40.0	40.0	40.0	40.0	40.0	-
	d	30.0	30.0	30.0	30.0	30.0	30.0	30.0	-
	e	22.5	22.5	22.5	22.5	22.5	22.5	22.5	-
	f	15.0	15.0	15.0	15.0	15.0	15.0	15.0	-
	g	7.5	7.5	7.5	7.5	7.5	7.5	7.5	-
	h	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-
	i	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-10.0	-
	j	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-
Resistivity Probes	a	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0
	b	16.3	16.0	16.0	16.0	16.3	16.0	16.0	15.0
	c	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Thermocouple Levels (Low Temp)	a	74.6	73.9	73.1	74.1	72.0	74.2	74.3	-
	b	40.3	40.1	39.9	39.8	40.3	40.1	40.0	-
	c	30.5	30.2	28.1	30.0	30.4	30.2	30.2	-
	d	25.5	25.1	25.1	25.0	25.4	25.0	25.2	-
	e	23.0	22.7	22.5	22.5	23.0	22.6	22.0	-
	f	20.5	20.1	20.0	20.0	20.2	20.1	20.1	-
	g	18.0	17.7	17.5	17.6	17.8	17.7	17.0	-
	h	15.5	15.2	15.1	15.1	15.4	15.0	15.1	-
	i	13.0	12.7	12.6	12.6	12.9	12.6	12.0	-
	j	10.7	10.1	9.9	10.0	10.5	10.0	10.0	-
	k	0.0	0.0	0.0	9.9	10.2	0.0	0.0	-
	l	-	0.0	-	0.0	0.0	-	-	-
Thermocouple Levels (High Temp)	a	-	-	-	-	-	-	-	-
	b	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-
	d	-	-	-	-	-	-	-	-
Gas Sampling Canister		-	19.0	19.0	-	-	-	-	-
Pressure Transducer		-	-	-	-	-	-	-	-
Tilt Meters	a	66.0	65.0	66.0	66.0	-	-	-	-
	b	55.0	55.0	55.0	55.0	-	-	-	-
Displacement Gauge	reference	-	-	-	-	-	-	-	-
	a	-	-	-	-	-	-	-	-
	b	-	-	-	-	-	-	-	-
	c	-	-	-	-	-	-	-	-
	d	-	-	-	-	-	-	-	-

was grouted over its entire length with a cement-fly ash grout pumped down a one-inch plastic hose fielded with the instrument string; this hose was withdrawn as the grout column rose in the well. Instrumentation leads were collated at the well head and fed via overhead cable trays to the recording trailer as shown in Figure 5. An overall view of the Phase 2 and 3 site is presented in Figure 6.

Two fielding points require emphasis. First, formation-property-matching grout was emplaced in a two-stage operation for Phase 1. Problems were encountered in adequately sealing the wells and emplacing the different grout formulations. The benefits of the matching grout did not outweigh the problems that were encountered in the complicated procedure, and a one-stage grouting procedure was adopted for Phases 2 and 3. Thermal and acoustic results show that the measurements are relatively insensitive to the grout properties. In fact, laboratory studies showed a significant shrinkage, cracking, and loss of strength of the grout upon heating above 100°C; ⁽⁵⁾ these effects have a greater effect on thermal conductivity and acoustic impedance than do formulation differences. Second, an unstable, sloughing zone was noted at this site at a depth of 150-180 ft, approximately at the water table. To overcome problems encountered in Phase 1, casing was installed to 180 ft in all instrumentation wells for Phases 2 and 3. An oversize hole was drilled through the slough zone, casing landed, and the remaining depth drilled by the standard bit through the casing. All wells were completed without problem by this improved, but considerably more expensive, procedure.

Fig. 5 - Phase 2 and 3 Site After Fielding; November 1975. View to the south from near Well S1; Well A in foreground.

Figure 6

(Photo from LERC)

The Phase 2 and 3 Experimental In Situ Coal Gasification Site Near Hanna, Wyoming. The wells to the coal seam are at the corners of the square indicated by the surface casing (clockwise from the lower left: Wells 6, 5, 7 and 8). Piping for air from the compressors to the site and for gas to the gas-flaring stack (under construction) are visible at the top of the picture. The two small white buildings are located over detonator Wells S1 and S2. White lines are cable trays connecting the instrumentation wells and surface arrays with Sandia's recording trailers. The remaining five buildings contain LERC's injection and production monitoring, gas analysis, office, light shop, and on-site computer facilities.

Two Sandia instrumentation trailers were used for the field data acquisition and recording. The acoustic, seismic, and electrical data were recorded in analog form. These procedures, summarized in Table V, resulted in a massive data digitizing and reduction effort which could not be performed on-site and resulted in considerable delay before the data were available for inspection. The thermal, tilt and displacement data were recorded digitally and were available on-site and real-time on printed paper tape. (In addition, 90 channels of thermal data and the in-seam pressure data were fed directly to LERC for recording on their computer-based system.)

Experience on Hanna II strongly emphasizes the need for computer-based field data acquisition and reduction systems which are capable of providing on-site, essentially real-time, analysis and display. Development of such systems is an objective of future efforts and all instrumentation techniques will be designed to incorporate this capability.

This section is meant to provide a broad overview of the instrumentation effort fielded on Hanna II. Additional detail will be found in the following sections for the different instrumentation techniques. Complete details can be found in the series of quarterly reports and other publications resulting from this program.

TABLE V
Summary of Data Acquisition for Phases 2 and 3

TECHNIQUE	D/A*	CHANNELS	FREQUENCY	OUTPUT
TEMPERATURE				
Digital Data Acquisition Systems	D	340	at least hourly	(a) Printed paper tape for immediate on-site use and permanent record. (b) Digital magnetic tape to Sandia for master file. (c) Daily digital scans by phone for current thermal file.
LERC	D	90	hourly ave.	Digital magnetic disk storage on LERC computer.
Thermocouple Resistance	D	15	hourly	Printed paper tape to Sandia.
PASSIVE ACOUSTIC	A	96	Two 5 min. scans/day	Analog magnetic tape to Sandia. Analog playback and digitizing of selected periods.
INDUCED SEISMIC	A	96	2/week	Analog magnetic tape to Sandia. Specific tapes selected for digitizing.
ELECTRICAL MEASUREMENTS				
Modified Schlumberger (MS)	A	96	every 4 hours	Analog magnetic tape to Sandia for digitizing and reduction.
Direct Excitation Electrical Potential (DEEP)	A	96	every 4 hours	Analog magnetic tape to Sandia for digitizing and reduction.
TILT AND DISPLACEMENT	D	83	hourly	Printed paper tape to Sandia.
	A	3	continuous	Paper chart to Sandia.
GAS SAMPLING	-	3 Wells	every 8 hours	Samples obtained manually and analyzed by gas chromatography. Analyses filed at site.
IN-SEAM PRESSURE	D	3	hourly ave.	Digital magnetic disk storage on LERC computer.

* D and A are digital and analog recording, respectively.

THERMAL INSTRUMENTATION AND DATA ANALYSIS

Thermal measurements and data analyses have revealed or substantiated many features of the process during all phases of the Hanna experiment: pre-ignition air injection, reverse combustion linking, gasification and cooldown. The major elements of the thermal instrumentation program include instrument specifications, data acquisition systems, data validation procedures, and data analysis. Each of these elements is important if the quantity and authenticity of information obtained from thermal instrumentation is to be maximized. Descriptions and assessments of the various elements of the thermal instrumentation program, including examples of field data and analytical results, are presented in this section of the report.

Instrumentation, Data Acquisition, and Data Validation

The locations of the thermal sensors in the overburden, coal seam and underburden during the Hanna II experiment are presented in Tables III and IV. Phase 1 was planned as a preliminary experiment and the temperature sensing array with 33 locations in four wells was sufficient to provide only limited spatial resolution in the vertical direction and to observe typical thermal histories at isolated points. The more extensive array with sensors at 169 locations in the 15 wells in Phases 2 and 3 allowed not only better vertical resolution and more thermal histories but also better definition of the velocity and direction of reaction zone propagation, the horizontal location of linking paths, and the lateral extent of the reaction zone at any level.

All of the thermocouples installed in Phase 1 and most of those in Phases 2 and 3 were of ANSI Type K (Chromel-Alumel) material. The elements were of 24 gauge wire insulated with MgO and sheathed with 1/8 o.d. Inconel-600 stainless steel. This material pair has a Relative Seebeck Coefficient of $21.4 \mu\text{V}/^\circ\text{F}$ at 32°F . It conforms to standard Type K characteristics within 4°F from 32°F to 535°F and within 3/4 percent up to 2300°F for short-term heating under favorable conditions.⁽⁶⁾ The agreement between sensors during quiescent periods was within 0.5°F . Although the elements do not melt at temperatures up to 2550°F , the combination in this wire size is recommended for prolonged use in protected environments at temperatures up to only 1600°F .

The in situ coal gasification environment is very inhospitable. High temperatures and a complex, changing gas composition (reducing and oxidizing conditions ahead and behind the reaction front, respectively, plus $0.1\% \text{H}_2\text{S}$) provide a very corrosive atmosphere. In addition, severe mechanical loads are imposed by caving and subsidence. These Chromel-Alumel thermocouples reliably measured temperatures during air injection, reverse combustion and the rapid increases to $1000\text{-}1900^\circ\text{F}$ during gasification. Lifetime of these sensors above

the 1000-1200°F range was uncertain, but ranged from an hour to a few days. The highest validated temperature observed was 1900°F; higher readings were recorded (2200-2400°F) but were invalidated by prior resistance or open circuit indications. In addition, multiple failures at low temperatures (< 1000°F) were observed in several cases and are ascribed to mechanical failure due to caving or subsidence.

"Classic," high temperature thermocouples, platinum-platinum 10% rhodium and tungsten 5% rhenium-tungsten 26% rhenium and sheathed with platinum or molybdenum and insulated with magnesia or beryllia, were fielded in addition to the other thermal strings in four wells during Phase 2. These thermocouple circuits were an order of magnitude more costly and were brittle, fragile and more difficult to field. These thermocouples failed also, often at relatively low temperatures, and did not perform as well as the majority of the Chromel-Alumel sensors.

Tip-branched, leg-branched, and conventional thermocouples were utilized during Hanna II and these configurations are schematically shown in Table VI. The branched circuitry provides additional measurements to be made and its theory is developed elsewhere.⁽⁷⁾ These unconventional circuits: (1) provide redundant temperature measurements through alternate circuit paths, (2) allow direct sensing of temperature differentials, and (3) uniquely permit the direct diagnostic measurement of spurious nonthermoelectric emf (noise) and loop resistance. The different measurands available to the different circuit pairs are also listed in Table VI. Thus, branched thermocouple circuits can be used to improve data return and allow validation of the thermal data; both of these factors are important for in situ thermometry applications.

Tip-branched thermocouple circuits are commercially available with the junction either isolated from or grounded to the metal protective sheath. Isolated junctions have been used exclusively in the present work to simplify noise isolation. The leg-branched circuits are not a standard commercial item and have been developed by Sandia. The branched measuring junctions were welded and cased in machined stainless steel cylinders. The casing was sealed to the Inconel-600 sheath of the thermoelements by stainless steel high pressure tube fittings. The cavity around the junction was tightly packed with powdered high-purity (99.4%) thermocouple-grade magnesium oxide insulation. This construction was employed because Hanna II schedules did not allow factory fabrication of a more desirable wholly-welded construction which has been developed subsequently. These prototype sensors functioned satisfactorily to 1900°F (validated data), and sensors exposed directly to step temperature changes had rise times on the order of minutes. Within the

TABLE VI

Thermocouple Circuits Employed in Hanna II Experiment

Thermocouple Circuit	Pair	Temperature At	Temperature Difference Between	Noise Loop	Homogeneous Loop Resistance	Heterogeneous Loop Resistance*
Conventional
1-2	A				✓
Tip-Branched
1-2	A				✓
	1-3	A		✓	✓	✓
	1-4	A				✓
	2-3	A			✓	✓
	2-4	A		✓		✓
	3-4	A				✓
Leg-Branched
1-2	B				✓
	1-3	A				✓
	1-4	A				✓
	2-3	B		✓	✓	✓
	2-4	A	A, B			✓
	3-4	A				✓

* Requires averaging two resistance readings with leads reversed (e.g., $1/2 (R_{1-2} + R_{2-1})$).

grout-filled instrument well, the junctions should respond to within 10 percent of a step in temperature at the grout-coal interface in less than two hours where the grout remains intact and within a few minutes where fissures or porosity have developed in the grout.⁽⁸⁾

Fielding procedures were summarized previously. For economy, a transition was made from metal-sheathed thermoelements to a 12-pair, direct-burial, compensating extension cable in a sealed and potted junction canister located about 50 ft above the coal seam. Another splice was made at a surface junction box to an extension cable that led to the recording facility which was located in a mobile instrumentation trailer. This surface junction was also found to be particularly useful for check-out and posttest measurements. Temperatures were recorded on microprocessor-based data acquisition systems. Multichannel data loggers performed cold junction compensation, analog-to-digital conversion, and non-linear scaling from emf to temperature. Temperatures were automatically sampled throughout the experiment at intervals from 15 minutes to 1 hour and were recorded with 0.1°F resolution. Spurious emf in the thermocouple circuits was substantial during the experiment, but noise rejection in the data loggers allowed recording of signals from competent thermocouples with sample-to-sample variations rarely exceeding 0.1°F during quiescent periods of stable temperature.

One-hundred channels of temperature data were recorded during Phase 1 and 370 channels of temperature and temperature-related data were recorded during Phases 2 and 3. Ninety other channels were recorded with the LERC computer, and these data were stored in a data base at the site. Data output was available in four forms: front-panel digital displays, printed paper tape, a telephone digital data link to Albuquerque, and digital data stored on magnetic tape. The immediate availability of the first two of these forms allowed open-loop process control and daily evaluation of operations and experiment trends so that modifications of measurement procedures could be promptly effected. The one-hundred channels of data which were transmitted daily directly to Albuquerque were available in a computerized format for plotting and interpretation throughout the experiment. The reel-to-reel magnetic tape recordings provided the data base for automatic data processing and subsequent detailed analysis.

Power outages and substantially unbalanced line voltages resulted from severe weather conditions and excessive local power demand on the three-phase commercial power for the data systems. Although voltage monitors, isolation transformers and 2-hour uninterruptible power supplies were utilized, intermittent power failures did occur. These failures and malfunctions of the data acquisition system produced easily recognized faulty scans of data at irregular intervals, but except for a few instances, these recording failures did not result in the loss of any data. The quality of the temperature data was excellent, but the task of data processing was significantly complicated by the faulty scans. Because of the

intermittent failures, it was necessary to edit the tapes to correct or exclude data records known to be meaningless. Editing was limited to correction of incorrectly recorded scan times or substitution of data from the back-up paper tape record. Data from defective sensors were not omitted from the comprehensive data base. The edited data were then available for critical examination to determine the validity of the temperature histories by comparison with the diagnostic data.

Analysis of the limited amount of diagnostic data recorded for branched thermocouples also allowed the validation of some of the Phase 2 and Phase 3 temperature data. The validation and correct interpretation of these data are critical because location and rate of movement of the gasification zone boundary are defined by these temperature responses. Invalid data can result from noise sources found not only within the thermal sensors but also in the data acquisition and reduction systems. Thus, both direct (redundant and differential temperatures, loop resistances, noise emf, and standard values) and indirect (auxiliary measurements, process parameters, site conditions and activities) evidence must be utilized in the data validation.⁽⁷⁾

Some aspects of data validation procedures can be illustrated by an analysis of the temperature, noise emf and circuit resistance data plotted in Fig. 7. These data were recorded for the level 5 feet above the coal floor in Well C during Phase 2. Examination of the noise emf record from Day 105 to Day 116 indicates that the temperature oscillations seen in the Recorder V data are the result of nonthermoelectric noise emf. Furthermore, the diagnostic data show no irregularities on Day 127 so that the abrupt temperature rise on this day is probably valid. The small increase in resistance at this time is consistent with circuit heating. In contrast, both the noise and resistance records show irregularities beyond Day 130. While it is clear that the circuit has failed by Day 141, the temperature data may be invalid as early as Day 130. The use of diagnostic data in this manner is important if misinterpretations of the temperature records are to be avoided as invalid segments of data frequently appear to be plausible.

Installation and Pre-ignition Air Injection Periods

During the installation and pre-ignition air injection periods, small but significant temperature changes were measured.⁽⁹⁾ Prompt, small temperature changes from the ambient value of $48 \pm 2^\circ\text{F}$ were observed as the grout immersed successively higher junctions. The presence of the grout was also indicated by the characteristic exothermic heating of the grout material upon setting which yielded temperatures as great as 128°F . At the beginning of the pre-ignition air injection phase, the temperature had decreased to approximately ambient values of $48-51^\circ\text{F}$. During the extended air injection period of Phase 1 (Days 97-139), small temperature elevations of 1 to 5°F near midseam in all the wells were observed.

Fig. 7 - Example of Diagnostic Data and Redundant Temperature Measurements.

These have been attributed to low temperature surface oxidation of the coal by the injected air. Temperatures in Well CC during this period are shown in Fig. 8; increases in the other wells were not as large.* In general, the promptness and magnitude of the temperature changes were proportional to measured well-to-well flow rates. Temperatures in the overburden did not change suggesting the lack of flow in these regions. Again during the Phase 2 air injection period, which was shorter (Days 88-93) and with lower flow rates, temperature increases of approximately 0.7°F were measured in wells along the linkage path. Thus, in situ flow distributions prior to ignition can be determined by precise (approximately 0.1°F resolution and stability) temperature measurements.

Phase 1: Results from a Limited Thermocouple Array

The limited thermocouple array fielded in Phase 1 precluded establishing the horizontal location of the linkage path or the gasification process. The array was sufficient, however, to provide limited vertical resolution and considerable insight into the mechanisms involved in in situ coal gasification. The temperature records from Well CC (Phase 1a), and AA (Phase 1b) are shown in Figure 9. More extensive discussion of Phase 1 results is found elsewhere. (3,9)

Fig. 8 - Temperatures During Directional Permeability and Pneumatic Linkage Test. (Thermocouple levels (feet) referenced to bottom of coal seam.)

During Phase 1a reverse combustion (Days 145-155), the only temperature change noted was an increase to approximately 200°F at the midseam location in Well CC. No thermal responses were measured in Well DD which was located four feet off the line between process Wells 1 and 3. (As a result of a 4-ft deviation in Well 3, the line joining Wells 1 and 3 at depth was separated by 4 ft from Well DD and about 1 ft from Well CC.) The following thermal responses indicated that reverse combustion was localized to a slender channel: the immediate temperature elevation at only one isolated level in Well CC, the absence of any prompt increases in Well DD, and the subsequent rapid increases in Wells CC and DD shortly after linking. Temperature histories in Wells AA and BB showed no evidence of temperature rises during Phase 1b linking. Subsequent, longer-term conduction

* Figure 8 also provides an example of the 0.1°F resolution in the thermal measurements.

Fig. 9 - Temperature Distributions in Wells CC and AA During Phase 1a and 1b, Respectively. (Thermocouple levels in feet referenced to bottom of coal seam.)

responses and gasification temperatures indicated that this link was formed below midseam and well off of the Well 1-2 line.

The temperature data from Wells CC and DD clearly indicate that gasification occurred initially at or below midseam. By the end of Phase 1a, gasification had extended to the coal ceiling near the injection well; Well DD temperature records indicated rapid temperature rises, often erratic temperatures, and abrupt thermocouple circuit failures attributed to the severe conditions and caving and subsidence. At Well CC, gasification temperatures were only measured in the lower half of the seam. During Phase 1b, the temperature history in Well AA showed gasification approached the ceiling, but the temperatures were lower and less erratic than in Well DD which indicated that gasification and subsidence were probably less extensive here than near Well DD. The Phase 1b gasification zone apparently did not extend directly from Well 2 to Well 1 because the maximum temperature recorded in Well BB was 110°F.

Following the termination of air injection, temperatures in Well AA decreased from 750-1000°F to 300°F in 80 days, and the temperatures in Well BB increased slowly from 60-110°F to 80-130°F as a result of conduction and/or convection from the hot, former reaction zone. Extrapolation of these decreases indicated that at least 8 months would be required for the in situ temperature to fall below 60°F.

Phase 2 and 3: Results from an Extensive Thermocouple Array

The fifteen instrumentation wells fielded for Phases 2 and 3 provided improved spatial coverage, both horizontal and vertical, and have yielded the best characterization of an in situ coal gasification process yet obtained. Qualitative presentation of the thermal data is useful in depicting the location of linkage and gasification near the bottom of the seam and advance of the reaction upwards in the seam and across the well pattern. A movie of the thermal data presents a graphic description; four frames from such a movie are shown in Fig. 10. Quantitative analysis of the thermal data can provide significantly more information. Results from such analyses are summarized in Table VII and discussion leading to these is presented here. Further information can be found elsewhere.^(10,11)

During Phase 2b reverse combustion linking, temperature increases above 100°F were observed in the order: Well D, O, E, B, G, and F. Temperatures in Wells G and F did not increase above 300°F until Days 114 and 118, respectively, and after temperatures greater than 1000°F had been observed in Wells B and E. These results indicate that the primary linkage path extended as an arc from Well 5, between Wells F and G, to Well 6. Low temperature responses were also observed in Wells A and C which were not located along the primary linkage path.

All low temperature linkage responses were analyzed by a heat conduction model⁽¹⁰⁾ and examples of the measured and calculated thermal responses are shown in Fig. 11. The early responses 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 and one level in Well A is consistent with a linkage path between these wells of equal size and temperature to that passing between Wells F and G, but one that begins to cool rapidly after about Day 106, the date of apparent linkage along the F-G path. Fig. 12 shows the relative position and size of the linkage paths with respect to the instrumentation wells.

The conduction analysis is most sensitive to the location of a heat source. The analysis places the center of the primary linkage path 5, 3.5, and 4 ft from Wells D, O, and G, respectively; and, similarly, the other path was 4 and 4.5 ft from Wells D and C, respectively. Of particular importance to the concept of linked vertical well gasification, there is no evidence of thermal override in the coal seam in all linkage data. The Well A-C path remains about 6 ft from the bottom of the coal seam and the primary Well F-G path about 5.5 ft from the bottom. The analysis cannot determine as accurately the temperature or diameter of the reverse combustion path. However, best

Fig. 10 - Four selected frames from the movie which presents thermal data from Phase 2b. Each plot shows the temperature (0-1000°F, x axis) for locations within the coal seam (0-30 ft, y axis). The eight thermal profiles are arranged to reflect the locations of Wells A-G and O.

TABLE VII

Analysis of Hanna II Thermal Data:

1. Determined the size (2.5 - 3.5 ft), temperature (900 - 1300°F) and position ($\pm 1/2$ ft) of reverse combustion linkage path.
2. Confirmed lack of thermal/bouyant override.
3. Indicated presence of second, partially-developed linkage path.
4. Characterized boundary motion during forward gasification; initial expansion near bottom of seam noted; vertical profile not constant.
5. Determined final boundary location from sensor responses outside boundary.
6. Characterized combustion front profile as being narrow (~ 2 ft) with high heating rates (5 - 9°F/min), and without an extensive pyrolysis zone.
7. Measured collapse and fracturing at least 30 ft into overburden.
8. Improved mapping of process as function of time by combining field thermal data and process model predictions.

Fig. 11 - Examples of Measured and Calculated Thermal Responses Utilized in Linkage Path Analysis.

Fig. 12 - Positions of Phase 2 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.

fits to the data consistently indicated temperatures of 900-1300°F and effective diameters of 2.5 to 3.5 ft. The results of this analysis as to temperature and size are consistent with a subsequent stability analysis performed on the Phase 2 linkage pressure and flow rate data (R. Gunn, LERC, private communication).

Similar heat conduction models were applied to data obtained during gasification. While caution must be exercised in applying these to processes where convective and radiative heat transfer certainly occur, the consistent agreement between calculated conductive responses and the field data indicate that conduction appears to be the predominate mechanism at least perpendicular to the main flow direction. For example, the location of one side of the reaction zone at the end of Phase 2 was found by conduction analyses of low temperature responses from Wells H, I, and J. Comparisons of calculated and measured temperatures from Wells H and J are presented in Fig. 13. The results indicated that the final boundary was 4-5 ft from Well J and 3-4 ft from Wells H and I. Typical boundary temperatures necessary for good agreement between calculated and measured responses were in the range of 1150°F to 1600°F.

An estimate of the boundary of the expanding gasification zone as a function of time can be obtained by combining temperature data and process model calculations. This procedure⁽¹¹⁾ yields boundaries produced by direct interaction between data and model calculations⁽¹²⁾ and provides not only the best estimate of such quantities as combustion front position, boundary velocities and sweep width, but also gives a direct measure of the validity of the predictive model. Although this procedure was developed primarily for use in analyzing Hanna IV data, the application of the mapping procedure to the Hanna II data resulted in boundaries shown in Fig. 14.

Fig. 13 - Measured and Calculated Thermal Responses Outside Reaction Zone Boundary at End of Phase 2.

Fig. 14 - Estimate of Gasification Zone as Function of Time by Combining Thermal Data with Process Model Calculations. (12)

The mapping procedure and conduction analyses provide a picture of how the process proceeded in the Hanna seam during forward gasification. Initially the horizontal growth is rapid at approximately the level of the linkage path, and the vertical growth is slower and confined to the region of the injection well and adjacent to the linkage path. During the later stages of gasification, the rate of horizontal extension low in the seam slows, and the boundary "pivots" about the points of furthest extent and moves toward the roof of the coal seam. A schematic diagram of the boundary movement late in Phase 2 is shown in Fig. 15.

The temperature distribution across the combustion front is useful for comparison with one-dimensional laboratory and modeling studies now being performed. A typical thermal response due to an advancing combustion front is shown in Fig. 16. These data provide an estimate of maximum heating rates ($5-9^{\circ}\text{F}/\text{min}$) and would seem to indicate that temperatures sufficient for gasification occur very near the pyrolysis zone. The temperature history in Fig. 16 can be converted to spatial distributions which are plotted in Fig. 17 and indicate a temperature increase from below 200°F to more than 1500°F in less than two feet.

Fig. 15 - Schematic Diagram of Reaction Zone Boundary Movement Near Well I.

Fig. 16 - Thermal Response Due to Advancing Combustion Front.

Fig. 17 - Spatial Temperature Distributions Obtained from Measured Data in Fig. 16 Assuming Two Combustion Front Velocities.

Information related to the effect of the process on the overburden and to the cool-down rate can also be obtained from the thermal data. For example, above the regions of most intense gasification, temperatures in excess of 200°F were observed as high as 45 feet into the overburden. These increases are significantly greater than any possible conduction response; and, therefore, it is likely that sufficient fracturing and partial collapse has occurred to establish convective gas paths to the upper levels. By the end of Phases 2 and 3, all of the thermocouples in the seam and some in the overburden in the area of the reaction zone had been destroyed. The few remaining thermocouples indicated that temperatures near the reaction zone had decreased to 200-300°F during the first nine months of the cooldown period.

Assessment and Future Development Areas

The preceeding discussions have presented an instrumentation approach for obtaining validated in situ temperature data and examples of the process characterization which can be obtained from the analysis of such data. It is clear that adequate thermal instrumentation is a necessity in the developmental stages of an in situ concept for energy recovery. Experience from the Hanna II experiment has led to developments in several areas which will be incorporated in Hanna IV and future geoenery experiments. These include a methodology for instrumentation well placement, standardized thermocouple designs, and improved field data acquisition and validation procedures.⁽¹¹⁾

Temperature measurements, while rich in information, are limited in both a short detection range (7-10 ft) due to the low thermal conductivity of coal and the cost of a diagnostic well. Adequate vertical resolution can be readily obtained, but horizontal resolution is costly. Therefore, it is important to design a well pattern which will maximize the information obtained for a given number of wells. The rationale for well pattern design will be based on the most important test objective, i.e., to define the position, velocity and vertical profile of the combustion front. Model calculations and field data will be used to predict combustion front locations as a function of time. Wells will then be placed where they will provide the most useful information for defining these front contours by intercepting the contours at a number of different locations along the perimeter to define their basic shape and at as many different times as possible to monitor how that shape varies with time.

In order to simplify procurement and reduce costs and fabrication time, the design of multipoint thermocouple assemblies has been generalized and standardized, and it is shown in Fig. 18. Modularized design of hardware and related software allows the general structure of the measuring system to be defined in most detail prior to firm definition of either the total number of wells or their specific locations. As experiment plans are

MODULAR IN SITU THERMOCOUPLE ASSEMBLY

SURFACE EXTENSION CABLE

1. Multiple Shielded
2. Thermoelectric Compensating Materials
3. < 16 Pair Per Cable

SURFACE JUNCTION BOX

1. Thermocouple Material Terminals
2. Wellhead Temperature Sensor
3. Waterproof Seal
4. < 48 Pair

SUBSURFACE EXTENSION CABLE

1. Armored, Direct Burial, Multiple Shield
2. Thermoelectric Compensating Materials
3. < 16 Pair Per Cable

EXTENSION JUNCTION BOX

1. Thermistor, Temperature: < 200 F
2. < 16 Pair Splice Core (Potted)
3. 2.5-In. Diameter

METAL SHEATHED THERMOELEMENTS

1. < 16 Conventional Junctions or
< 8 Tip-Branched Junctions, or
< 16 Leg-Branched Junctions, or
< 16 Mixed Types
2. Thermoelectric Material: Chromel-Alumel
Used; W5%Re/W26%Re, Pt/Pt10%Rh, etc.
Possible
3. Sheath: Stainless Steel and Inconel Used;
Hastelloy, Tantalum, etc. Possible
4. Insulation: MgO Used; BeO, Th₂O₃ etc.
Possible
5. Temperature: < 2000°F
6. Spacing: A and B, Variable

INSTRUMENT WELL

1. 4 to 8-In. Diameter Hole Filled With
Thermal Matched Grout

Fig. 18 - Modular In Situ Thermocouple Assembly.

made definite, only a few elements of additional information are then required to finalize the instrument design. This standard thermal sensor design will also be an integral part of a complete diagnostic well module which will be defined for use in various geoenery experiments.

In the Hanna II experiment, thermal data were recorded with microprocessor-based data loggers which were capable of making one predetermined type of measurement such as voltage or resistance on hard-wired pairs of leads. Although data from branched thermocouples were recorded successfully, the inflexibility of this equipment did not permit the convenient measurement of temperatures and associated diagnostics useful in validating all Hanna II data. Therefore, to simplify the acquisition of these data, a combinatorial multiplex (COMUX) switching system will be developed for thermal data acquisition on Hanna IV. All temperature, resistance and noise emf measurements offered by the branched thermocouple

circuit can be acquired with this computer-controlled switch and multi-function meter included in the minicomputer-based field data acquisition system. Thus, real-time acquisition, validation, analysis and display will be available at the test site.

There are some questions about underground coal gasification that thermal data have not been able to answer. In particular, two temperature distributions have not been well defined: (1) detailed combustion front temperature profiles in the elevated temperature regions ($> 1500^{\circ}\text{F}$) and (2) temperatures in the seam following the passage of the oxidation zone. Thermal instrumentation has not been able to provide a consistent picture of these regions because of the many thermocouple failures that occur under these conditions. However, it must be noted that closer examination of the temperature records seem to indicate that it is possible that no consistent temperature histories for these regions exist; because, after the coal has been pyrolyzed, the temperature is controlled by convective heating and local flow conditions which probably vary significantly within the process. Improved survivability will be sought by investigating different materials and designing experiments to determine the mechanisms of thermocouple failure.

IN-SEAM GAS SAMPLING AND PRESSURE

Long-line gas sampling techniques have been evaluated as a way of obtaining diagnostic information during in situ coal gasification. Gas sampling canisters with tubes leading to the surface were emplaced in selected instrumentation wells. Gas samples were withdrawn through the tube, collected at the surface, and analyzed via standard gas chromatographic techniques. At times samples were not being withdrawn, a pressure transducer installed on the line at the surface provided a static measurement of the local pressure in the coal seam.

The objective of the gas sampling measurements is to correlate local gas species and their concentrations with temperature and position in advance of, within, and behind the reaction zone. By such local sampling, it is intended to distinguish between chemical reactions in the primary reaction zone and reactions which might occur enroute to customary wellhead sampling at the surface.* This information is to provide an improved understanding of the in situ reaction chemistry. In addition, pressure measurements can allow pressure gradients and flow distributions to be determined. Pressure data are particularly important during periods of high pressure air injection and reverse combustion linkage when pressure gradients are large and cannot be assumed to be uniform and linear.

*It is recognized that changes in composition can occur due to reaction, cooling, and condensation along the length of the sampling tube.

Also, water influx into the system affects both the effective process volume and overall gasification reactions and depends upon the balance of hydrostatic pressure (and flow rates) and the applied pressure at a given location.

These measurements were a joint Sandia-LERC responsibility. The design, fabrication and fielding of the gas sampling canister and its associated sampling tube, surface fittings, and pressure transducer were performed by Sandia; gas sampling and analysis, pressure recording, and data analysis were done by LERC.

Special canister design was required for the in-seam end of the sampling tube since the entire instrument string was completely grouted in the uncased instrumentation wells. The canister design is shown in Fig. 19. The canister contains gravel to maintain permeability near the end of the tube; metal mesh, cloth covering, and internal pressurization were used to keep grout out during the grouting operation. Two explosive squibs were mounted on the outside of the canister during fielding and were detonated after the grout had set to shatter the grout annulus and allow communication with the coal seam. (The squibs also provided convenient reference signals for the passive acoustic technique.)

A high pressure nitrogen purge and sampling system was used at the surface in order: (1) to stimulate spontaneous gas flow in cases where the canister and sampling tube were water-filled, (2) to allow a reverse purge after sampling to prevent plugging of the 1/4 in. diameter sampling tube by condensed organics, and (3) to monitor gas flow so as to clear the sampling tube to insure a representative gas sample for analysis. Various sets of sampling conditions can be defined based upon different hydrologic pressure and flow conditions and applied injection pressures during pretest, linking and gasification phases of the test. After detonator firing, the water-filled canister and sampling tube could be blown free with nitrogen, but became resaturated when gas pressure was removed. During high pressure air injection during reverse combustion, once the tube was cleared, it remained clear for the remainder of the test. Thus, gas samples could be obtained from regions at ambient temperatures and well away from the reaction zone. Apparently water influx rates at the Hanna site are low and do not allow the establishment of equilibrium hydrostatic pressure during the test. Application of these sampling measurements may be more limited under different hydrologic conditions.

There was pretest concern that the withdrawal of hot gas samples might cause spurious temperature rises at thermocouples in the grout column above the canister. In practice, no effect was noted for the one- or three-times-per-day sampling intervals used.

(a)

(b)

Fig. 19 - Gas Sampling Carister. (a) As Fielded; Note Explosive Detonator Near Left Edge and Just Below Center. (b) Interior Details.

Ten gas sampling canisters were fielded: one on Phase 1 (Well BB) and nine on Phases 2 and 3 (Wells B-G, I, J and O). Well BB remained unaffected during Phase 1 and gas sampling was not performed. In Phases 2 and 3, communication with the coal seam was obtained initially in Wells C and D; communication was also obtained in Well F after gasification in that region. Apparently in the other cases, the pressurization was not sufficient to keep out the grout during completion and the sampling tubes were presumed to be plugged with grout. (An improved canister design has been grouted and tested under pressure in the laboratory and will be used on future experiments. Improvements are in the areas of reduced size, positive plastic coating and sealing, and the use of a continuous "multi-tube" to the surface to allow 3 canisters per well.)

The results from Wells C and D are sufficient to demonstrate feasibility of the long-line sampling technique to obtain diagnostic information during in situ coal gasification. A summary of data for selected periods is shown in Table VIII. Well 5 data were obtained at the surface meter run on the production gas stream. Pressure data are approximate average values during the selected periods. The continuously recorded in-seam pressures in Wells C and D were used by LERC to assess linkage and possible regions of low permeability. Apparently, valid gas samples and pressures were obtained even when the canister was at ambient temperatures indicating that drying of the coal was not prerequisite to communication with the reaction zone. Gas samples were also obtained even when high temperatures were measured at and above the canister location and it was assumed that the canister had burned away and samples were being obtained from the end of the sampling tube at some higher, unknown location.

Differences in both gas composition and pressure are evident. Particularly noticeable are: (a) the pressure gradients during reverse combustion linking and gasification, (b) the oxygen-depleted "air" samples for Days 102-105 which indicated that air flow was occurring at locations remote from the reaction zone, (c) the oxygen gradient on Day 116, and (d) the relative differences and ratios between H_2 , CH_4 , CO and CO_2 which reflect compositional changes due to the shift and other reactions.

An assessment of the technique can be summarized by the following: (1) Long-line gas sampling techniques can be used to obtain in situ gas compositions and concentrations and in situ pressures during in situ coal gasification. (2) The hydrology of the Hanna site was favorable for this technique; operation under higher hydrostatic pressure (greater depth) and water influx will have to be assessed. (3) Improved design features (reduced size and proof-tested sealing) have been incorporated into units for future field testing. (4) The gas sampling system will be combined with the modular in situ thermocouple system in a specification of a diagnostic well for in situ thermal processes.

TABLE VIII

In-Seam Gas Compositions and Pressures Obtained From the Gas Sampling Canisters*

	WELL	Gas Compositions (Volume Percent)									Pressure psig	Injection Pressure at Well 6	Temperature at Canister
		Hydrogen	Nitrogen	Oxygen	Argon	Carbon Monoxide	Methane	Carbon Dioxide	Sum C ₂	Sum C ₃			
Days 102-105** Linking	5	12.1	61.3	1.0	0.8	5.2	4.0	15.1	0.4	0.1	2		-
	D	-	81.0	17.9	1.0	-	0.1	0.1	-	-	128	225	50°F
	C	-	80.8	17.9	1.0	-	0.1	0.3	-	-	132		50°F
Day 116 Moderate Injection	5	18.4	46.6	1.3	0.6	12.6	6.1	13.3	0.7	0.4	16		-
	D	17.9	53.1	2.8	0.7	14.7	5.7	4.4	0.7	0.2	75	125	50°F
	C	5.7	62.3	8.6	0.8	9.1	4.0	8.9	0.5	0.1	20		50°F
Days 136-137*** Gasification	5	16.4	48.8	0.4	0.6	17.0	5.1	11.3	0.5	0.1	44		-
	D	13.9	52.1	0.5	0.6	18.3	4.6	9.4	0.5	0.1	78	87	57°F
	C	14.4	51.8	0.1	0.6	18.7	4.8	9.1	0.4	0.1	80		300°F
Day 146 Gasification	5	14.6	52.1	0.4	0.6	12.8	5.3	13.6	0.5	0.1	42		-
	D	14.3	49.6	0.1	0.5	11.8	8.0	14.8	0.7	0.2	70	82	350°F
	C	8.7	63.8	0.5	0.8	7.5	2.1	16.4	0.1	-	70		Burned Off

*Canisters located 19 ft above the bottom of the coal seam

**Average of three measurements

***Average of two measurements

SUBSIDENCE MEASUREMENTS: TILT AND DISPLACEMENT

Tilt and displacement gauges were fielded in selected instrumentation wells to obtain diagnostic information on the response of the first 50 ft of overburden directly above the coal seam. Subsidence to the surface was not expected for the limited extent of the Hanna II test and these instrumentation techniques were intended to give information on the early stages of subsidence. Tilt measurements were to measure bending and deformation in two relatively competent sandstone strata above the coal seam. Differential displacement gauges were designed to measure displacement, both upwards and downwards, between four different anchor elevations and a reference canister approximately 75 ft above the seam. It was hoped that the mechanism and extent of near-overburden subsidence could be determined through the combination of tilt and displacement data.

The tilt gauges were fielded in the canister pictured in Fig. 20. Two-axis, angular potentiometric vertical indicators manufactured by Humphrey, Inc. were used which had a range and resolution of $\pm 10^\circ$ and $\pm 0.5^\circ$, respectively. Sensitivity was sacrificed in favor of a 500°F operating temperature. The canister contained a compass with electrical readout at the surface for determining canister orientation after grouting. The canister was not clamped directly to the messenger cable but was hung by nylon cord to improve freedom of movement. A six foot section of bronze cable was spliced in the messenger cable near each location, so that the compass would not be distorted. Fourteen canisters were fielded: two each in Wells B, C, F, H, I, J, and K. Three canisters failed during the grouting procedures and cable leakage was suspected; different cables were used on the other canisters. Satisfactory electrical performance was observed throughout the test or until the canister was destroyed.

Fig. 20 - Canister Containing Two-Axis Potentiometric Tilt-Meters and Orientation Compass.

The displacement gauges pictured in Fig. 21 consisted of four telescoping tubes, each with an anchor to be located approximately 5, 20, 32.5 and 54 ft above the coal seam. Small wire cables connected each anchor with linear potentiometers (Fig. 21c) located in the reference canister (Fig. 21b) located approximately 75 ft above the coal seam in a thick sandstone formation. The anchors were fastened to the messenger cable with low-load (80 lb) shear pins and fielded with all other instrumentation. A 50-inch full scale deflection would be measured for each anchor; in addition, the lower anchor was also fastened to a potentiometer with a 15 ft full-scale deflection. Displacement gauges were fielded in Wells C, E and G. (Well C contained all varieties of instrumentation and thus was the most complex fielding activity on this test.) Satisfactory electrical performance was observed throughout the test.

The tilt and displacement data were recorded as the resistances of the span or range and wiper of a potentiometer for each measurement. The resistances were recorded hourly over a six month interval on a digital scanner and printed on paper tape. Daily scans were entered into a master computer file for calculation and plotting. The lowest anchor on the Well C displacement gauge and the X and Y axis of the lower tilt gauge in Well B were analog recorded on small-span strip chart recorders to obtain better temporal resolution.

All tilt and displacement data (Days 72 through 278) have been plotted and examined. It is concluded that these techniques as fielded did not detect the degree of roof collapse suggested from other indirect evidence (thermal data, passive acoustic source locations, etc.). No conclusive tilt readings were obtained. A 1.2 ft displacement of the lowest anchor in Well C was the largest displacement measured and is shown with similar records for Wells E and G in Figure 22.

Table IX presents the day that the different tiltmeters failed; this can be taken as indirect evidence of either thermal or mechanical failure due to roof collapse at that location. Data from the canisters of the displacement gauges in Wells C, E and G appeared valid throughout the test. These are located ~ 75-77 ft above the top of the coal seam and suggests that collapse did not extend to that height at these locations.

Failure of these techniques is attributed to: (1) the large number of cables and other instrumentation fielded in the same well resulting in a reinforced grout column and (2) the uncertain sensor-grout-formation interfaces. It is clear from these results that tilt and displacement measurements must be made in wells dedicated to each technique; this is a costly requirement. The loss of the grout's strength above 100°C also requires direct sensor-formation contact via pins or spreaders if detection of movement at elevated temperatures is required.

Fig. 21 - The Displacement Gauge Fielded on Hanna II: (a) Being Assembled, (b) The Reference Canister, and (c) Linear Potentiometers in Canister.

Fig. 22 - Displacement Records for the Lowest Anchors in Wells C (O), E (X), and G (Δ).
A change in position of + 0.1 equals a displacement down of 1.5 ft.

TABLE IX
Tiltmeter Failure; Evidence for Roof Collapse
Extending to that Location

Well	Location*	Last Day (±1)**	Comment
B	37 ft	208	Analog records
	25 ft	-	
C	41 ft	236	
	25 ft	206	
F	41 ft	Survived	Failed pretest
	25 ft	-	
H	36 ft	216	
	25 ft	200	
I	36 ft	Survived	
	25 ft	202	
J	36 ft	Survived	Failed pretest
	25 ft	-	
K	36 ft	Survived	Failed pretest
	25 ft	-	

* Above top of coal seam.

** Measurements made through Day 278.

Future subsidence instrumentation activities will focus upon the displacement measurement via a modified slifer technique. This technique was originally developed to measure collapse of cavities produced by underground nuclear detonations. In this method, the effective length of cable is determined by time-domain reflectometry. This will allow a "continuous" measure of the remaining unbroken length of cable as subsidence would cause a tensile failure and shortening of the cable. As subsidence progresses upward in discrete steps, as suggested by the Hanna stratigraphy, the upper boundary of subsidence would be determined as a function of time. The cable is designed for use at ambient temperatures (as thermal conduction is very poor) and contains protrusions at one foot intervals. It will be fielded and grouted in its own well without a messenger cable or other reinforcing cables or instrumentation.

An assessment of the tilt and displacement techniques can be made: (1) The techniques as fielded did not detect the degree of subsidence in the overburden suggested by other instrumentation techniques. Failure is attributed to reinforcing of the grout column by cables and other instrumentation field in the same well and uncertain sensor-grout-formation interfaces. Feasibility of these techniques has not been demonstrated. (2) Future development will focus upon monitoring the upwards progression of subsidence via a modified slifer or time-domain reflectometry technique; the sensor cable will be fielded in a well dedicated to that measurement.

ELECTRICAL MONITORING TECHNIQUES

The basis for developing electrical methods for remote monitoring is that the electrical resistivity of coal varies by several orders of magnitude during in situ gasification. The resistivity of the water-saturated, virgin coal in the Hanna area is $\sim 200\text{--}250\ \Omega\text{-m}$, while the over- and underburden resistivities are both $50\ \Omega\text{-m}$. Laboratory measurements of the resistivity on three samples of Hanna coal as a function of temperature are shown in Fig. 23⁽¹³⁾. The resistivity of the dry, unaltered coal at room temperature is $\sim 10^9\ \Omega\text{-m}$. Upon reaction and devolatilization, the resistivity of the coal decreases continuously from $\sim 10^5\ \Omega\text{-m}$ at 400°C (750°F) to $\sim 1\ \Omega\text{-m}$ 700°C (1300°F).

Two electrical techniques are under investigation as a means to monitor the reaction front during in situ gasification: a modified Schlumberger (MS) technique which is a galvanic resistivity method⁽¹⁴⁾ and a direct excitation electrical potential (DEEP) technique which is essentially a dynamic "misse-a-la-masse" method.⁽¹⁵⁾

Fig. 23 - Observed Resistivity for Three Coal Samples During Heating to 700°C. Significant observations from this study⁽¹³⁾ are: (a) the resistivity of the dry coal is approximately 10^9 ohm-m at room temperature, (b) there is a decrease of resistivity by about 10 orders of magnitude with increasing temperature to 700°C, (c) there are strong dielectric polarization effects at low temperatures, (d) apparently there is a thermally activated decrease of resistivity with temperature with an activation energy approximately 0.4 eV, and (e) no strong dependence of resistivity on atmospheric oxygen content was observed.

The MS technique is schematically illustrated in Fig. 24. The hot conductive reaction region distorts the applied current lines and changes in the electrical potential are measured by fixed potential probe arrays at the surface and in the instrumentation wells. The current electrodes are outlying wells symmetrically located on either side of the test region. As will be shown, the linkage path can be detected using the MS technique when a major component of the applied current lies in the linkage direction; the experimental results are in agreement with model calculations.⁽¹⁶⁾

A schematic of the DEEP technique is shown in Fig. 25, where the current electrodes are a process well (generally the production well) and an outlying well. The potentials are measured by fixed probe arrays at the surface and in the instrumentation wells; these can be the same arrays used for the MS method. Prior to linkage and gasification the current lines radiate from the process well and equipotential contours are concentric about the process well. During the linkage and gasification process, the hot conducting coal in contact with the production well becomes part of the current electrode, and thus, the geometry of the current source varies with the shape, extent, and movement of the reaction zone. In this case the current lines and equipotential contours become distorted. As will be shown, the equipotential contours from the DEEP data indicate the position of the linkage path, the movement of the reaction front, and the extent of the process; the experimental results are in agreement with model calculations.⁽¹⁷⁾

Fig. 24 - Schematic Illustration of the MS Technique.

Fig. 25 - Schematic Illustration of the DEEP Technique. (Current lines and equipotential contours are mutually perpendicular.)

Only the MS technique was used on Phase 1, while both the MS and DEEP methods were used on Phases 2 and 3; however, the MS results for Phase 1* and the DEEP results for Phase 2b form the basis for this assessment.

Both techniques have advantages and can be easily fielded together. Since both the MS and DEEP methods use the same current drive system, potential probe array(s), and data collection hardware, these methods may be employed sequentially by using a simple arrangement to switch current from an outlying well to the production well. The MS technique has a fixed applied current geometry and is thus relatively amenable to quantitative analytical modeling. The DEEP technique produces larger measurable potentials making it more sensitive to the process, but the changing current electrode geometry, the basis for the technique, yields a very difficult analytical inverse problem to characterize the reaction zone given an observed potential distribution.

Instrumentation

For Phase 1, 18 surface potential difference measurements were made from a 10 ft by 10 ft grid of 23 potential probes shown in Fig. 2. Potentials between each east-west pair were measured; the apparent resistivity is this potential difference divided by the injection current and multiplied by a geometrical factor. The probes were emplaced below frost-line at a depth of 5-6 ft. The probes contained a copper sulfate solution which passed through a ceramic frit to insure a conductive, nonpolarizing contact with the earth. In each of the four instrumentation wells, 1-ft long, 2-in angle aluminum potential probes were installed at locations given in Table III.

For Phases 2 and 3, the potential probe array, along with the subsurface instrumentation well location, are shown in Fig. 4. Because of problems in keeping the copper sulfate porous pots filled during Phase 1, a simple metal probe was adopted. These surface potential probes were 18-in long, 1/2 in diameter, stainless steel rods and were buried beneath the frost-line at depths of 6-7 ft on generally a 10 by 10 ft spacing. A set of four reference probes was located approximately 100 ft to the north of the well 5-6 line as shown in Fig. 4. Potentials measured by these probes were used to minimize potential changes measured by the array which were not process related (e.g., telluric currents, electrical noise, etc.). In addition to the surface probes, three potential probes, similar to those fielded for Phase 1, were installed in each of the instrumentation wells at the locations given in Table IV.

*The current electrodes were fielded perpendicular to the Well 5-6, 7-8 lines in Phases 2 and 3 in anticipation of monitoring the line drive and thus MS results were relatively insensitive.

The current source electrodes for the MS technique consisted of 30 ft, 7 in diameter cased wells. For Phase 1, the two current drive wells were located 750 ft either side of the geometrical center of Wells AA, BB, CC, and DD shown in Fig. 2 in the eastwest direction. The two current drive wells for Phases 2 and 3 were located 750 ft either side of Well G along the A-C-F-G line shown in Fig. 4.

The current electrodes for the DEEP technique were the production well, Well 5 in Fig. 4, and an outlying well located approximately 590 ft west of Well 5 in a direction 12°N of the Well 5-6 line. This outlying electrode was also a 30 ft, 7 in diameter cased well.

Fig. 26 - Block Diagram of the Instrumentation System for the Electrical Measurements.

A block diagram of the frequency modulated (FM) data recording system used in Phases 2 and 3 is shown in Fig. 26. (The recording system used in Phase 1 was similar.) Capacitors were installed on each electrode circuit to eliminate strong background DC potentials on the order of 70 mv. Every four hours, the programmer was initiated by a timer and an associated time code generator synchronized to WWV. The programmer controlled the recording cycle in the following sequence: (1) start tape recorder, (2) initiate 3 cycles of current to the MS drive wells (each cycle was 2 seconds positive and 2 seconds negative with an amplitude ~ 5.7 amps peak-peak), (3) switch current lines and initiate 3 cycles of current to the DEEP current drive wells (each cycle was 2 seconds positive and 2 seconds negative with an amplitude of ~ 0.85 amps peak-peak), and (4) switch amplifier inputs to the calibrate signal line and initiate one cycle of calibrate signal (again 2 seconds positive and 2 seconds negative and 10 mv peak-peak). The 96 channels of data were FM recorded on 14-track magnetic tapes. For Phase 1, the recording cycle was similar to that given above except the MS current level was ~ 18 amps peak-peak, sequence (3) was not used, and only 32 channels of data were recorded.

Since data were collected at least every 4 hours (occasional hourly data were collected), each tape could store only 3-4 days of data. Tapes were sent to the Sandia Laboratories Data Reduction Center where they were digitized at a 40 Hz rate, compared to the calibrate level to produce a normalized voltage or "resistivity," and stored on digital magnetic

tapes. The data were examined and obviously bad data due to tape dropout, recorder malfunction, VCO and amplifier drift, bad calibration signal, etc., were deleted and were replaced by a linear interpolation between good data points.

Phase 1 Results: MS Technique and Modeling

Large decreases in resistivity during Phase 1a were measured by probes in the vicinity of the 1-3 line on Day 157; this decrease was not noted near Wells 2, AA, and BB. This resistivity change occurred two days after the linkage was established as defined by large changes in the injection flow rate and pressure and corresponded to the time of the temperature increases at midseam in Wells CC and DD. The probable reason for the delay of the electrical indication following actual linkage was that the temperature of the initial carbonized coal link was not sufficient to give a low resistivity path. With the beginning of gasification, the high temperatures in excess of $\sim 650^{\circ}\text{C}$ (1200°F) were obtained.

Resistivity contour plots for Phase 1a are shown in Fig. 27 where the resistivities have been normalized to their pre-experiment values. A value of the normalized resistivity greater than 1.0, equal to 1.0, and less than 1.0 correspond to resistivities which have increased, remain unchanged, and decreased, respectively, from their pretest value. The figure shows the normalized resistivity contours just prior to and just after electrical

Fig. 27 - Computer-Generated, Normalized Resistivity Plots From Surface Probe Array Showing Phase 1a Linkage. (Resistivity normalized to pre-experiment values so a value of 1.00 corresponds to no change. The array location relative to wells is shown.)

linkage for Phase 1a. A resistivity saddle appears along the 1-3 line after electrical linkage as predicted by the model calculations to be discussed below. This saddle indicates the linkage path is along the Well 1-3 line and the path is confirmed by the thermal measurements. Due to equipment failure, no MS resistivity data were collected during the latter part of Phase 1a gasification period.

Normalized resistivity contour plots for selected days during Phase 1b are shown in Fig. 28. The electrical indication (decrease in resistivity near Well 2) of linkage during Phase 1b took place on Day 204 which was one day after linkage was indicated by the injection parameters, but before rapid temperature rises were measured in Well AA. The contours for Day 206 show an increase in the resistivity in the vicinity of Well 2 and the development of a resistivity saddle in the upper left hand corner of the array. The contours for Day 218 show a general increase in the resistivity along with the resistivity saddle between Well 2 and the 1-3 line. Probable causes of the general resistivity increase of the area were: (1) a large area was affected leading to a larger island of dry, unaltered, high resistivity coal, and (2) even though the void may be surrounded by hot conducting coal, the large void led to an increased electrical resistance of the coal seam and thus increased apparent resistivity. The resistivity saddle is probably centered over the cavity surrounded by hot, carbonized coal resulting from gasification in Phase 1b. This result is consistent with thermal data from Wells AA and BB as to the location of the linkage and gasification during Phase 1b.

A three-dimensional resistance network model has been utilized to describe the galvanic resistivity measurements. In this assessment, only a brief outline of the technique and an illustrative example of results will be given as more extensive coverage is given elsewhere.⁽¹⁶⁾

The overburden, coal seam, and underburden are divided into finite elements with an appropriate resistivity assigned to each element. The current divergence condition yields the result that the total current entering each node is zero (the sign convention used is that currents entering a volume are positive while those leaving are negative). This leads to a system of linear algebraic equations for the potentials at the nodal points in a resistance network. Nodal points are connected by appropriate conductances in the x, y, and z, directions. Symbolically, the system of equations is written as

$$S \phi = I \quad (1)$$

where S is the square conductance matrix, ϕ is the column matrix for the potentials at each nodal point, and I is the column matrix for the current injected into the nodal points from an external source.

DAY 200

(before linkage)

DAY 204

(after linkage)

DAY 206

(after linkage)

DAY 218

(after linkage)

Fig. 28 - Computer-Generated, Normalized Resistivity Plots From Surface Probe Array from Phase 1b. (Resistivity normalized to its pre-experiment value so a value of 1.00 corresponds to no change. The array location relative to wells is shown.)

For the model calculations here, there is a current source and a current sink at the surface of the earth; no current flows through the surface of the earth except at these points. The horizontal boundaries are assumed to be far enough away so that no current flows through these boundaries. An insulating basement is assumed. Finally, no current flows through the plane connecting the current source and sink; this symmetry was utilized in the calculations. The effects of the conducting casings of the injection and production wells are simulated as the casings provide a low resistance path from the coal seam to the surface of the earth. For conduction in the vertical direction, the resistance of the materials in a volume of earth and that of the well casings are treated as resistances in parallel. The effects of the casings are ignored for conduction in the horizontal direction.

The potentials obtained from the model calculations are used to calculate the electric field everywhere. The electric field, E_x , is defined as $|E_x| = |\Delta\phi|/|\Delta x|$ where $\Delta\phi$ is the potential difference between two points a distance of Δx apart. In plotting $|E_x|/I$ vs. x in Fig. 29, the value for $|E_x|$ is plotted midway between the positions of the potentials used to determine $\Delta\phi$; I is the current. The calculated points are connected by straight lines. Here VB denotes E_x for the wet, virgin coal, UC denotes E_x for the island of the dry, unaltered coal created by air injection, and the numbers denote E_x for various lengths of the low resistance, carbonized path as it grows within the island of dry unaltered coal from the production well (P) to the numbered surfaces 1, 2, 3, etc. The letter L denotes the electrical linking of the injection and recovery wells via the low resistance, carbonized coal. The insets in the figure show the location of the wells and the low resistance path. The electric field component E_x is calculated on the centerline between I and P and 3 m off centerline as shown.

The apparent resistivity is proportional to $\Delta\phi/I$; thus, $|E_x|/I$ is proportional to the apparent resistivity. The behavior of the apparent resistivity would be similar to that of $|E_x|/I$ shown in Fig. 29.

Inspection of Fig. 29 shows that when electrical linking has occurred, there is a saddle in the electric field (or apparent resistivity). The lows in $|E_x|$ are near the wells and the crest of the saddle is centered between the wells and over the low resistance path. This saddle feature is observed in the field data when the injection and production wells were electrically linked during Phases 1a and 1b as shown in Fig. 27 and 28, respectively.

Fig. 29 - Model Calculations of $|E_x|/I$ Versus x . The inset shows location of the hot, carbonized coal path, location of injection (I) and production (P) wells and the traverses of E_x on and off centerline.

During Phase 1a gasification, the volume of the cavity expanded so that the combustion front moved away from the injection well, Well 3. Indication of this increase in volume of the cavity near the injection well is given by the temperature rises at the 25-ft and 30-ft levels in Well DD. With this growing cavity, good electrical "contact" was lost between Well 3 and the combustion region; this led to an increase in the resistivity approximately two days after the electrical linking. An illustration of when the low resistivity path does not connect the well casings can be found in Fig. 29 for curves 1-4.

Phase 2 Results: DEEP Technique and Modeling

Equipotential contour plots for the DEEP technique are available for Phase 2b (Days 100 to 153) and form the basis for this assessment. A movie of the equipotential contours has been made to depict the evolution of the process, and four selected days are shown in Fig. 30 to illustrate the behavior of the DEEP results. Each plot in Fig. 30 is the average of at least six scans made by using part of the surface probe array. Because of the 96 channel recording limitation, only those probes in and north of the Well H-K line were used for Phase 2b. The locations of the process wells (05 and 06) and the instrumentation wells in this region (A-K and O) are shown on the contour plots.

To minimize effects on the data for changes not associated with process-related effects, the potentials were referenced to potentials measured by the outlying reference probes shown in Fig. 4. The corrected potential at a time t for the i -th probe, $V_i^c(t)$, is given by

$$V_i^c(t) = \frac{V_i(t)V_{ref}^B}{V_{ref}(t)}, \quad (2)$$

where $V_i(t)$ is the measured potential at the i -th probe at a time t , $V_{ref}(t)$ is the measured reference potential, and V_{ref}^B is an average potential base on Day 100.

From Day 100 to 115, the equipotential contours remained similar to those shown for Day 101 in Fig. 30; the activity summary for Phase 2b is given in Table I. Since current lines and equipotential lines are mutually perpendicular, the production well (Well 5) was the apparent major source of current during this time. Thus, the progress of the reverse combustion reaction is not clearly indicated, although small changes in the magnitude and shape of the equipotential contours were observed.

Fig. 30 - Surface Equipotential Contour Plots of DEEP Data for Selected Days. (Potentials are referenced to outlying Probes. The well positions are indicated on the plots.)

Following the reverse combustion linkage of the production and injection wells, the temperature of the coal increased (as observed in the in situ thermal data) such as to make the coal conductive along the entire linkage path and electrically link the process wells. The equipotential contour plot for Day 118 is representative of the contour plots for Days 116 to 128. This represents a period of moderate injection flows (see Table I). For Day 118, the surface projection of the apparent major current source is located near Well E. These electrical data for this period indicate that the initial reaction zone between Wells 5 and 6 was off the 5-6 line and close to Wells E, F, and O; this observation is in agreement with thermal data^(10,11) and downhole potential measurements.

Fig. 31 - Downhole Equipotential Contour
Plots of DEEP Data. (Units are
millivolts/amp. This plot is for
data taken at midseam on Day 117.)

Following an increase in air injection on Day 129, the potential contours changed to those shown for Day 129. It is apparent that the major source of current was then near Wells 6 and B, where it remained until Day 150. However, shifts in the contours and the potential gradients were evident during Days 129-150, the period of major gasification and enlargement of the reaction zone. Day 140 shows essentially symmetric response about the Well 5-6 line; at later days, the contours become slightly distorted towards Well A. Again, the observed shift is consistent with the thermal data as well as with the seismic-acoustic data.

$$\phi(\vec{x}) = \rho j \int_S dS' G(\vec{x}, \vec{x}') \quad , \quad (3)$$

where $G(\vec{x}, \vec{x}')$ is the half-space Green's function given by

$$G(\vec{x}, \vec{x}') = (1/4 \pi) \left\{ [(x-x')^2 + (y-y')^2 + (z-z')^2]^{-1/2} + [(x-x')^2 + (y-y')^2 + (z+z')^2]^{-1/2} \right\} \quad (4)$$

Here ρ is a uniform earth apparent resistivity and j is the constant current density leaving the surface S , where S is the surface of the well casings and reaction zone. In Eqns. 3 and 4, $\vec{x}$ is the field point and $\vec{x}'$ is the source point. Details of the calculations and results will be given elsewhere. ⁽¹⁷⁾

The calculations show that for a reaction zone with a small surface area connected only to the production well, the production well is the apparent major source of current, and the equipotential contours are concentric about the production well. This type of behavior was observed from Day 100 to Day 115. The behavior of the contours for Day 118 in Fig. 30 can be simulated by taking the current source to be the lower portions of Wells 5 and 6 with a connecting conducting reaction zone. In the field, the upper portions of the production and/or injection wells may not contribute to the current for either or both of the following reasons: (1) the near-surface (above the water table) earth resistivity is higher than the lower portions, leading to a smaller amount of current leaving the upper portions of the process wells; (2) the hot gases flowing through the production well heat and dry the surrounding material, leading to an increase in its resistivity, and hence, a lower current flow in these regions.

The appearance of the contours for Days 129 and 140 in Fig. 30 is indicative of the production well no longer being a major current source, at least near the surface. Due to the potential highs near Wells B and 6, the major source of current for Days 129 and 140 appears to be a large reaction zone near Well 6 (the injection well) along with at least portions of Wells 6 and B.

The current leaving the hot volume of coal is apparently shunted to the surface by the conductive casings of the injection and/or instrumentation wells. (The latter were cased to a depth of 150-180 ft to control a slough zone during instrumentation fielding.) As the major source of current moves within the coal seam, the apparent center of the source measured at the surface appears to shift from well to well as illustrated by Days 118 and 129.

From approximately Day 140 to 150 the values and location of the equipotential contours did not change appreciably. This is indicative of a more-or-less constant surface area of the reaction zone, i.e., a constant current electrode size and shape. Analysis of the thermal data as presented in Fig. 14 and 15 indicates that the reaction zone near the bottom of the seam reaches maximum extent ahead of the reaction zone higher in the seam. For this case, the vertically-projected surface area of the reaction zone would not change appreciably during the time the upper portion of the seam was being gasified. The surface area would be dominated by the shape of the gasified volume of the lower portion of the seam and the values and locations of the surface equipotential contours would remain nearly constant.

It is clear that a qualitative, continuous picture of the process can be obtained that will give information on symmetry, location of the linkage path, extent of the gasified area, and movement of the process. The behavior of the equipotential contours is consistent with model predictions. However, the inverse problem of using the DEEP potential data to quantify the boundaries of the reaction zone is difficult and is under development. One technique under investigation consists of using surface potential data to determine the current densities on one or two grid planes which simulate the actual reaction zone current source. The solution for the current densities requires solving a system of linear algebraic equations; however, the system of equations is too ill-conditioned to solve using the more conventional methods. To solve for the current densities, a non-negative linear least squares algorithm is used for an overdetermined system of equations with a constraint condition.

To test the validity of the DEEP analysis technique, potential data were calculated using Eqns. 3 and 4 for a simulated current source. Results of an illustrative calculation are shown in Fig. 32 for two current grid planes adjusted to give a minimum of the residual. For the calculated potentials, the current source consisted of the lower 89% of the production and injection well casings and the combustion zone current source shown by the dashed lines. The solid lines are contour lines of equal current density as determined in the upper grid plane. The upper and lower grid planes are approximately at the depths of the top and the bottom of the source, respectively. The region of high current density coincides with the actual current source. The results shown do not include the effects of errors that would appear in actual field data; the effects of errors on the analysis capability are currently under investigation.

Fig. 32 - Calculated Contours of Equal Current Density. (P and I indicate production and injection wells, respectively, and numbers on the contours are current density $\times 10^5$. Dashed lines indicate the actual shape of the current source used in the calculation.)

Conclusions and Assessment

The electrical techniques under investigation are a modified Schlumberger (MS) technique and a direct excitation electrical potential (DEEP) technique. Comparison of the thermal results, which give a direct picture of the process, with both the MS and DEEP results (Phases 1 and 2b, respectively) shows: (1) if the applied current has a component in the direction connecting the process wells, the location of the linkage path is detectable using the MS method; (2) that the equipotential contours produced by the DEEP method give a qualitative picture of the symmetry, motion, and extent of the reaction zone. Both techniques can yield a real time, two-dimensional representation of the process which could be incorporated into a process control system.

Further work is needed in the analysis of both MS and DEEP data to delineate the process from experimental field data. Linear inverse and least-squares fitting of model parameters are techniques under investigation to quantify the process. Preliminary results for DEEP data are encouraging and it is anticipated that by using these inversion techniques, the geometry of the UCG process can be defined. A complete assessment of the limitations and resolution limits for the electrical techniques is not available at the present time. However, initial results do suggest that the center of the reaction zone, the symmetry of the process with respect to the process wells,

and a reasonable estimate of the process boundary can be determined. It is also clear that very accurate field data will be needed to resolve the boundaries of the process.

Even though the development of an inversion analysis capability has not been completed, the normalized resistivity plots from the MS method and the equipotential contour plots of the DEEP method, along with comparisons to model calculations, do provide information about the process and can be used to map the reaction zone. The feasibility of using these electrical techniques for remote monitoring of in situ coal gasification has been demonstrated.

PASSIVE ACOUSTIC MONITORING TECHNIQUE

Seismic-acoustic studies on the Hanna I experiment indicated that process-related noise could be detected by geophones emplaced in nearby wells.⁽¹⁾ These results suggested that the source locations of these acoustic signals could provide a means for remotely mapping the dynamic process. While such location techniques have been used to map zones of increasing stress in deep mines,⁽¹⁸⁻²⁰⁾ this work marks the first known attempt to monitor in situ coal gasification. Preliminary signal characterization and locations were done during Phase 1⁽²¹⁾ and the more extensive geophone array of Phases 2 and 3 has provided a larger data base for assessment of this technique.^(22,23)

Instrumentation

Ten Geospace 20D vertical axis, velocity-type geophones with a sensitivity of 0.6 volts/in/sec were fielded in each of the instrumentation wells by lowering them on a cable and grouting them into the wells. These geophones exhibit a reasonably flat spectrum from 10-1000 Hz. The grouting procedure provided good coupling of the geophones to the walls of the boreholes and hence to the surrounding medium. Geophones were located below, in, and above the coal seam at the locations given in Tables III and IV for Phase 1 and Phases 2 and 3, respectively. Locations for Phases 2 and 3 were determined on the basis of providing maximal spatial coverage for the induced seismic technique; an exception was Well G for which geophone locations were selected in order to measure the vertical attenuation of passive seismic signals. The most useful geophones were those in the overburden as this was the source of most activity and as sensors and cables in the coal seam were lost at temperatures above 250°F.

The geophone outputs were recorded during two five-minute intervals daily throughout the experiment. These signals were amplified and preserved on a standard fourteen track magnetic tape instrumentation recorder using voltage-controlled oscillators with sensitivities and bandwidths chosen to be consistent with sensor response. Approximately 160 analog magnetic tapes were recorded in conjunction with Phases 2 and 3 alone and were returned to the Sandia Data Processing Center for oscillograph playback, visual inspection and selection of events for digitizing and filtering, and subsequent analysis.

Results from Phases 1, 2, and 3

Three basic seismic signal types were observed during the Phase 1 test. Two types, continuous noise, Fig. 33, and burst-like signals, Fig. 34, were not useful for process monitoring because of an insufficient number detected and/or a waveform too complex to accurately determine compressional or shear wave arrival times. The third, and potentially most useful, type observed consisted of relatively high frequency, pulse-like signals with clearly evident first arrivals. An example of this type, and one with an "intermediate" signal-to-noise ratio, is shown in Fig. 35; the differences in time-of-arrival are readily apparent.

Fig. 33 - Type 1 Passive Signal: Continuous Burning Noise.

Fig. 34 - Type 2 Passive Signal: Bursts of Acoustic Noise.

The frequency of occurrence of the latter signal type for four linkage and gasification periods are given in Fig. 36. A clear correlation exists between seismic activity and gasification. As these records are taken from arbitrary five minute intervals each day, it is evident that a large number of signals with a range of amplitudes occur daily to form the basis of this technique.

A linear-least squares technique was adopted from several options which determine the spatial origin of seismic-acoustic signals propagating within the earth. (18,24)

The basic approach was to assume a region homogeneous in velocity, use the geophone which first receives the acoustic signal as a reference, eliminate the non-linear terms involving the unknown source coordinates, and then minimize the resulting

expression:
$$f(x,y,z) = \sum_{j=1}^N (A_j x + B_j y + C_j z - E_j)^2$$
, where A_j , B_j , C_j , and E_j

are functions of the geophone coordinates and the differential arrival times. A complete description of this technique and its inherent errors are presented elsewhere. (23) The procedure followed in the source locations was: (1) to locate the event based on the use of N arrival times as input to the source location code, (2) to reduce N to determine if location is sensitive to particular channels, and (3) to relocate the source, and if the solution moved, take the solution with minimum error.

Fig. 35 - Type 3 Passive Signal: Discrete Signals.

Fig. 36 - Frequency of Occurrence of Discrete Passive Signals During the Hanna II Experiment. (Gasification periods indicated by arrows. Records are not available for all days.)

Only a limited data base was available from Phase 1 and only nine source locations could be determined as shown in Fig. 37. A total of 195 events (1950 channels) were selected from the oscillograph records from Day 132 to Day 155 in Phase 2b for digitizing and detailed analysis. This data base forms the basis of this assessment and includes date, time, signal-to-noise ratio, peak amplitude and location, source location (if possible), number of channels (out of ten) used in location, and whether the signal was detected at the highest geophone.⁽²³⁾ A total of 95 source locations could be determined are shown in Fig. 38.

All source locations are in the overburden and tend to occur over those regions where thermal and electrical data indicate the most gasification activity occurred. The fact that these events are subsidence related is indicated by Figs. 37 and 38c. Sources occur in a fairly incompetent layer of silty sandstone and shale and are the results of the failure of this overlying layer to support the overburden when the underlying coal is removed. The discrete nature of the signals suggests that the signals are caused by cracks or sags in this overburden. Thermal cracking is also a possibility as a correlation between activity and high temperatures ($> 300^{\circ}\text{F}$) at the top of the coal seam appears to exist from the limited example shown in Fig. 39. Comparison of the burn front contours at the 30 feet level given in Fig. 14 with Fig. 38b further supports this correlation between coal removal at the top of the seam (actually complete utilization of the coal seam for the Hanna II test) and localized acoustic activity.

Fig. 37 - Source Locations for Selected Discrete Signals Recorded During Days 168 and 171, Phase 1a.

(a)

(b)

(c)

Fig. 38 - Locations of 95 Discrete Seismic Events During Phase 2b: (a) Relative Number of Events, (b) Plan View of Source Locations, (c) Profile of Activity Projected Onto Well 5-6 Plane.

Assessment and Development Directions

Discrete passive seismic signals observed during in situ coal gasification are useful for estimating process extent and movement and provide a measure of the extent of subsidence above a burning coal seam. Determining the utility and ease of application of the technique is more difficult and requires a working demonstration of instrumentation designed to automatically detect process and locate the seismic events.

There are several factors which tend to prevent this technique from being readily extrapolated to remote surface geophones arrays and these are inherently related to the time-frequency requirements for locating a signal source in three dimensions. Gaardner⁽²⁵⁾ discusses in detail the estimation of the location of a signal source and the errors associated with the estimate. His results indicate that: (1) if one has an estimate of the signal onset time (synchronous case) reliable estimates of the distance and direction to the source can be found for distant sources, (2) in the asynchronous case only good estimates of the source direction are possible for distant sources, (3) for signals occurring outside the dimensions of an array the errors dramatically increase, (4) the errors for signals located within the array are dependent on the array geometry, and (5) the spatial location errors are related in a complicated fashion to the time-of-arrival errors. Simulation results for the Hanna II experiment indicate that a time-of-arrival accuracy of 0.25 msec is required for a spatial resolution of 5 ft.

Fig. 39 - Source Locations for Some Discrete Passive Signals. (Number given indicates height, in feet, above the coal seam.)

This result is for geophones very close to the coal seam; signals observed in geophones further away from the seam will have lower frequencies, and the resulting locations subject to errors as indicated by Gaardner. Regardless of the loss in signal bandwidth caused by attenuation of the higher signal frequencies, increased errors will become evident as the first arrivals become buried in system noise. Hence, source signal strength is also very important.

A measure of the varying intensity of the signals observed in the near-process geophone array during Hanna II is presented in Fig. 40. This figure is a plot of the number of events observed within specified signal-to-noise ratio bands in the near-process array. The signal-to-noise ratio is independent of channel gain and this plot gives a measure of the amplitude range of events observed. Further, the uppermost channel in Well G (approximately 70 feet above most events) was useful for source locations purposes in 33 of the 195 events selected; these were part of the set of 42 events observed in the lower channels which had signal-to-noise ratios of 1000 or more. This result implies that approximately 1/6 of the signals observed during the Hanna II Phase 2b experiment obtained by recording during 5 minute intervals daily, and observed in a geophone 70 feet above most events, were useful for source location purposes. Approximately 5% of the total number of signals observed in this uppermost channel in Well G had signal-to-noise ratios which would allow for signal detection another 70-100 ft from the process. The conclusion is that attenuation of the signals and their low levels cause the maximum sensing distance of the passive acoustic technique to be approximately 100-200 ft. Using this result and an average

Fig. 40 - Observed Number of Signals as Function of Signal-To-Noise Ratio in Strongest Channel.

rate of one event/minute it is estimated that a geophone array located approximately 100-200 ft above a gasification process would detect approximately 100 useful events daily during the gasification period when cracking and subsidence occur in the overburden. This result provides the motivation to develop instrumentation to process in real-time passive seismic events for the upcoming Hanna IV experiment.

The basis for the recording scheme is a result of Gaardner's study on the accuracy of the source location operation. Specifically, for the far field, Gaardner's study indicates poor source-distance resolution if a signal onset time is not available. These errors are reduced if

an onset time is made available by using a near process geophone as a "trigger". In addition, recording this near-process signal will allow for matched filter detection in the upper array channels. Since the matched filter provides the maximum signal-to-noise ratio over all other filters this procedure will not only minimize spatial errors but will optimize noise reduction.

One method of detection which can be used to capture the reference of trigger pulses is based on an estimate of the signal-to-noise ratio in the reference or trigger channels. The procedure is to:

- (1) estimate the noise power, σ_r^2 , in a signal-free interval,
- (2) take a new sample and iteratively estimate present power in the channel with

$$\sigma_{n+1}^2 = (n\sigma_n^2 + g_1^2)/(n + 1)$$

where g_1 is the digitized geophone output at the i^{th} point in time, and

- (3) if $\sigma_{n+1}^2 > K\sigma_r^2$ record event, otherwise set $n = n + 1$ and return to step 2.

This algorithm was used in the processing of the seismic signals for the induced seismic technique and is discussed further elsewhere. (26)

In summary, discrete passive seismic signals observed during in situ coal gasification are useful for estimating process extent and provide a measure of subsidence activity above the burning coal seam. It is estimated that 5% of these discrete events will be detected in a geophone array located at a maximum distance of 200 feet from the spatial origins of the activity. Instrumentation which processes these data and implements a simple algorithm for signal detection is under development. For 5-ft accuracy in event location, this instrumentation and associated algorithms for signal processing must provide a time-of-arrival accuracy no less than 0.25 msec.

INDUCED SEISMIC MONITORING TECHNIQUE

The basic philosophy behind the induced seismic instrumentation technique is that changes in the elastic parameters of the media caused by the gasification process are observable in terms of changes in seismic signal parameters such as velocity (time-of-arrival) and amplitude. Initially, the concept was that if a pretest record of induced seismic signal arrival times and first-peak amplitudes could be defined and the ray paths between source and geophones determined, then the process could be delineated when those ray paths with altered parameters were deleted from the pretest ray path diagram. It was also found that reflecting boundaries can be determined from observation of signal records and their power spectra for sources and sensors located near the process.^(26,27) Both downhole source-to-downhole geophone and downhole source-to-surface geophone configurations were examined. The former to critically examine the technique under most favorable conditions, and the latter to assess the technique as to its potential as a remote monitoring technique.

The results show that a borehole-to-borehole method based on transmission timing and reflection timing models can be used to characterize the edge of the area affected by the process. Changes in time-of-arrival along specific ray paths provide the spatial correlation to the process in both analyses. Diffraction effects were found to play a significant role, particularly in the amplitude analysis.^(26,28) A complete description of the induced seismic technique, complete with the diffraction, reflection and refraction models, signal processing algorithms, source radiation patterns, site seismic characterizations, and additional results, is being prepared.⁽²⁶⁾

Instrumentation

The same geophones were used for the passive acoustic and induced seismic measurements and consisted of ten geophones in each of the instrumentations wells (Fig. 3 and Table IV). In addition, 15 geophones were buried at a depth of 20 ft at locations shown in Fig. 4 to assess the borehole-to-surface configuration.

Induced seismic data were collected before, and twice-a-week during, Phases 2a and 2b. (It was intended to collect data through Phase 3, but a gas leak from the coal seam into Well S1 occurred at the end of Phase 2b which precluded further use of this well.) Strings of twelve detonators (located at -40, -30, -20, -10, 0, 7.5, 15, 22.5, 30, 40, 50, and 60 ft with respect to the coal seam floor) were lowered into Wells S1 and S2 and detonated in sequence by an automatic timer. These wells were cased with fiberglass-cement casing, cemented in place, and water filled.

A 96-channel, 14-track analog FM tape recorder was used to record the resulting seismic signals. The procedure for recording and processing the induced seismic data was as follows: (1) select 96 geophone channels for recording, (2) calibrate with an accurate reference voltage, (3) fire detonators sequentially while recording, (4) return tape to Sandia's Data Reduction Center, (5) reverse FM tape operation with discriminators, (6) select time window for digitizing, (7) digitize 96 channels at 10 kHz for length-of-time window for 12 detonators fired in each hole, (8) create special CDC 3100 tape for special processing of large volume of data on CDC 6600, and/or (9) create digital plots or other tapes compatible with other Sandia computers. A computer code was developed to characterize the signals by their time-of-arrival and first-peak amplitude and time and was applied to the majority of the signals. In addition, visual comparisons of pre- and posttest signals were often necessary for complete analysis. An example of the signals and their spectra are shown in Fig. 41.

Results from Phase 2

The volume of data, as well as time constraints on the analysis, precluded the interpretation of the entire data set. Thus, a set of data considered sufficient to fulfill experimental goals was processed and interpreted. This set included Phase 2a pretest and linkage data and five selected days during Phase 2b: pretest (Day 85), linkage (Day 125), and gasification (Days 132, 139, and 146).

The data interpretation is based on the models mentioned previously. Specifically, the interpretation depends on variations in the timing and attenuation characteristics of the process on transmitted and reflected signals caused by the gasification process. Reflection and transmission analyses were used to monitor the vertical and lateral extents of the burn, respectively. In the interpretation of the reflection data, it was very difficult to determine the onset of a particular phase due to interference from other arrivals, since the available wavelengths were on the order of the geophone separation. Thus, two methods were used to find the reflecting boundary: a spectral technique as well as visual scanning of the records. The reflection interpretation evolved from records generated by detonators located 60 ft above the coal seam floor and recorded by geophones within and above the seam. The records used in the shadowing (transmission) analysis were from all twelve detonators (with emphasis on the lower detonators) and from the entire geophone array.

Phase 2a. Reference data were collected during November, 1975 and were used to form a baseline set of times-of-arrival and first-peak amplitudes and times to be used for comparison purposes with process-related data. Variation of these parameters within the reference set were examined to determine the sensitivity of the technique to measurement errors. Velocities obtained from the induced seismic data were in good agreement with velocities in the vicinity of the geophones observed from well logs. To estimate the

Fig. 41 - Acoustic Signals and Spectra for Reference and Gasification Periods at Midseam in Well C.

standard error in the measurement of time-of-arrival and first-peak amplitudes, redundant sets of data were collected which included data for different detonators and geophones. This estimate provided a measure of the minimum detectable change in a comparison of reference with process data. Eighty-six samples of first-peak amplitudes were used to estimate a one-sigma variation of 8.8%. This result indicates that any amplitude variation less than 9% is not meaningful. Comparisons of time-of-arrival data from the data reduction code with visual estimates indicate that an accuracy of 0.1-0.2 msec in the arrival times could be obtained.

To detect the linkage during Phase 2a, signals observed along ray paths for all detonators and selected geophones in Wells L, M, and N were analyzed, based on data from two different days using both Wells S1 and S2 as source boreholes. The times-of-arrival, times of first peak and first-peak amplitudes were obtained from the data reduction code. The observed amplitudes were scaled both by the calibration value for the different days and an average amplitude for all geophones on a given day for each detonator to account for day-to-day variations in detonator strength. In all of the data, the variation did not greatly exceed the expected variation of $\pm 9\%$ observed in the background data. Reflection analysis was not carried out on these data. Phase 2a linkage was not detected.

Phase 2b, Pretest Data. Additional reference data were obtained for the Phase 2b portion of the gasification experiment to guarantee that effects related to the Phase 2a linkage and an improved detonator cable assembly had not altered the signal parameters thereby making Phase 2b process-data interpretation more difficult. One set of pretest data is shown in Fig. 42 (and is to be compared with a similar presentation for Days 132 and 146). Records in this format were useful for visual interpretation but do not allow for accurate time-of-arrival or amplitude estimates; a computer code operating on the digitized signal provides these data.

These reference data offered an opportunity to compare the reflection analysis with the known structural model which is implied by the density and velocity log obtained in source Wells S1 and S2. Three geophones located in the coal seam in the Wells A, C and F were used in the reflection analysis. These geophones were located at 22.5, 15, and 7.5 ft with respect to the bottom of the coal seam. The basic reflection model shown in Fig. 43 indicates the various waves which are source as well as interface generated. The top of the coal should be revealed by the P-S mode converted wave, while the bottom will be exposed by the PPP reflected wave. For the reflection study, the uppermost detonator in S1, located about 60 ft above the bottom of the coal seam, was used. From reflection studies, the coal seam floor (h_L in Fig. 43) was determined to be within 2 ft of its position given by well logs.

PRETEST
MARCH 25, 1976
DAY 85

GEOPHONE LOCATION IN FEET ABOVE
COAL SEAM FLOOR

60 50 40 30 22.5 15 7.5 0 -10 -20

This figure shows a scale for geophone locations. The scale is in feet above the coal seam floor, with values: 60, 50, 40, 30, 22.5, 15, 7.5, 0, -10, -20. An arrow points from the text 'GEOPHONE LOCATION IN FEET ABOVE COAL SEAM FLOOR' to the scale.

Figure 42. Observed Induced Seismic Records. (Lowest detonator in Well S1 (40 ft below coal seam) to geophones in instrumentation wells. Amplitudes normalized to given values for each signal.)

Fig. 43 - Ray Paths for Reflected and Converted Signals for a Given Detonator-Geophone Pair.

$$\begin{aligned} \rho_3 &= 2.6 \text{ g/cm}^3 \\ \alpha_3 &= 10,000 \text{ ft/sec} \end{aligned}$$

Phase 2b Linkage. Transmission studies on these data were not conducted because of difficulties encountered in the digitizing of field records during this period. A reflection analysis indicated changing boundary conditions near the floor of the coal seam, but no direct indication of the linkage path was evident.

Phase 2b Gasification. Clearly detectable variations in the transmission and reflection signal parameters are evident in the data from Day 132. Examination of the Day 132 data relative to the reference period involved comparison of first-peak amplitudes and times-of-arrival for the twelve detonator sources fired in S1 and signals observed at geophone locations in Wells A, B, C, D, E, F and G. A slight velocity decrease (2-4%) in unaffected regions was evident and is attributed to removal of water from the natural fracture system of the coal or overburden. Large velocity and amplitude decreases are definitely observed when paths intersect the process. This fact is substantiated by Fig. 44, which provides the changes in times-of-arrival and first-peak amplitudes from the reference period to Day 132. In the figure, differential time and amplitude measurements are provided for the indicated S1-to-instrumentation-well profile after firing detonators at 40 ft beneath the coal seam. The data are given for observations in geophones at specific heights above the coal seam floor. The amplitudes for both days were normalized to an unaffected geophone, and then differences were calculated to make

Fig. 44 - Signal Parameter Changes Above Affected Zone for Firing Lowest Detonator; (a) Normalized Amplitude Changes and (b) Times-of-Arrival Changes in Milliseconds.

the first-pulse profiles. The interpretation is that for detonator-geophone paths which are shadowed by the process, significant time-of-arrival changes (> 1.0 msec) and amplitude variations are noted.

The results of the seismic interpretation from transmission and reflection analyses for Day 132 are presented in Fig. 45 and indicate the lateral and vertical extent of the process. This interpretation is substantiated somewhat by thermal observations; a 200°F isotherm is indicated on the figure.

In another analysis, time-of-arrival and first-peak amplitude changes were averaged within three categories of source-geophone paths; these results are given in Table X. A 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. Large velocity and amplitude changes are definitely observed when the paths intersect the process. Generally, however, the standard deviation of these averages are on the order of 50 to 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.

Fig. 45 - Delineation of the Reaction Region on Day 132 by Induced Seismic Methods and Comparison with Thermal Data. ($< 70^{\circ}\text{F}$ measured at points a and b.)

TABLE X

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)

Amplitude data were difficult to work with after Day 132; time-of-arrival data appeared most sensitive. Times-of-arrival comparisons for Days 139-132 and 146-139 as well as use of the reflection model provided an interpretation of process motion and extent for these days. The results for Day 132, 139, and 146 are presented in Fig. 46. The points shown correspond to the intersection of the shadowing and reflection boundaries similar to those shown in Fig. 45. The actual maximum extent of the process for all three days is not determinate from the seismic data, except that gas leakage in S1 was noted on Day 148. In general, the results of the seismic interpretation agree reasonably well with thermal information, but seismic changes are detectable somewhat ahead of the gasification front (Figs. 14, 45 and 46). The exact correlation between detectable seismic signal parameter changes and the process effects causing these changes could not be determined in this study.

Assessment

The induced seismic instrumentation technique here has been shown to be useful for estimating the lateral as well as vertical extent and motion of an in situ coal gasification process. The results are in reasonable agreement with estimated burn front contours obtained from thermal data. Experience gained from analyzing the induced seismic data collected during this test allows an assessment of the technique as applied to in situ coal gasification to be defined.

Fig. 46 - Minimum Boundary of Affected Coal Found By The Induced Seismic Technique.

The basic goal of the induced seismic instrumentation program was to provide estimates as to process motion and activity. Limitations of this technique are either based on theoretical considerations or the method of data collection. The major theoretical consideration is diffraction. Diffraction effects play a role that is not fully understood for all possible void geometries. The modeling of spherical voids at a single frequency indicates that there are both shadow and enhancement zones and that the first pulse effects are difficult to characterize without accounting for all frequencies in the source pulse. ^(26,28)

Diffraction requires further modeling along these lines to fully understand process effects on the signal parameters. Other considerations are that: (1) deconvolution techniques are limited by the problem

dimensions (e.g. geophone spacing) in their ability to resolve reflectors, (2) synthetic seismogram techniques can be applied only if accurate models for the layering, gasification process and source pulse are known, and (3) sophisticated interpretation of reflection timing and spectrum records is required. The limitations of present instrumentation or data collection include: (1) the use of expensive, nonrepeatable detonator sources, (2) analog signal recording requiring extensive data reduction and digitizing, (3) vertical axis geophones which respond to signals on an axis normal to the direction of propagation, and the (4) limited range due to signal attenuation.

Several theoretical and instrumentation problems can be minimized in future tests by using a "chirp" type source in the source borehole much as the Vibroseis is used for surface reflection studies. For this application, a "high frequency" source would be swept from some frequency range over a several second interval. The characteristics of the medium would be found via a deconvolution technique by using the auto- and cross-correlation functions of the source-receiver pair signals. This technique would: (1) improve signal-to-noise ratios significantly thus improving amplitude estimates, (2) minimize borehole damage, (3) allow for averaging of many signals to further improve signal-to-noise ratios at greater distances, (4) provide for excellent source repeatability, (5) allow frequency selectivity over selected frequencies or bands, (6) and in general provide for more sophisticated analysis. A drawback of this approach is the need to develop high-powered, borehole sources for transmission over long distances.

The above limitations and assessment apply to monitoring the process from borehole-to-borehole. The induced seismic technique could be extended by monitoring from borehole-to-surface, surface-to-borehole, and/or surface-to-surface. However, each of these approaches has additional limitations as well: more severe diffraction problems, decreased resolution due to the attenuation of higher (> 100 Hz) frequencies, lowered overall signal-to-noise ratios, and the effects of surface mechanical noise due to compressors, stacks, drilling, etc. Downhole-to-surface data obtained in Hanna II confirmed the presence of these problems to the extent that detailed analysis of these data were not performed.

Due to the number of factors affecting amplitude and resolution, the general surface-to-surface seismic reflection techniques were not investigated on Hanna II. However, recent advances in high-resolution, seismic geophysical techniques may find application in the future.⁽²⁹⁾ Diffraction will also play a role in the seismic reflection approach, albeit not a clear one. It is felt that the most difficult part of the seismic reflection problem is the estimation of the process edge. Given signal frequencies as high as 150 Hz, errors as great as 25 to 30 feet could result. Hence the reflection technique cannot be used for process monitoring, but may be useful for posttest delineation of the process.

FURTHER DEVELOPMENT: INSTRUMENTATION FOR HANNA IV

The previous sections have presented assessments for the instrumentation techniques fielded on the Hanna II in situ coal gasification experiment. Further development of these techniques along the lines discussed will be pursued in conjunction with LERC's Hanna IV experiment which is now in the construction phase and is scheduled for ignition in 1977.* The Hanna IV test will investigate linkage and gasification at well spacings of 100 and 150 ft.⁽²⁾

Both diagnostic and remote monitoring instrumentation will be fielded and these are summarized in Tables XI and XII, respectively. Thirty diagnostic wells will be fielded; this is twice the number of wells to cover seven times the area with respect

* The Hanna III experiment was a limited gasification test with environmental objectives conducted by LERC in Summer 1977.

TABLE XI

DIAGNOSTIC INSTRUMENTATION TECHNIQUES FOR HANNA IV

<u>Description</u>	<u>Well and Sensor Locations</u>
<u>THERMAL</u>	
Branched Thermocouple Circuits	12 Levels in Each of 30 Diagnostic Wells.
Exploratory Materials	Selected Locations. (Feasibility Study)
<u>GAS SAMPLING</u>	
Long-Line Gas Sampling from In-Seam Canisters	3 Canisters in Each of 20 Diagnostic Wells
<u>IN-SEAM PRESSURE</u>	
Pressure Transducer at Surface on Each Gas Sampling Line	3 Transducers for Each of 20 Diagnostic Wells
<u>SUBSIDENCE</u>	
Modified Time-Domain-Reflectometry Technique	1 Special Well to Contain Cables; Essentially 1 ft Resolution. (Feasibility Study)

TABLE XII

REMOTE INSTRUMENTATION TECHNIQUES FOR HANNA IV

<u>Description</u>	<u>Well and Sensor Locations</u>
<u>ELECTRICAL</u>	
Direct Excitation Electrical Potential	296 Probe Surface Array (65 x 115 m), 5 Reference Probes, and One Probe Above the Coal Seam in Each of 30 Diagnostic Wells.
Modified Schlumberger	
<u>PASSIVE ACOUSTIC</u>	
Vertical - Axis Geophones	4 Located Above the Coal Seam in Each of 6 Diagnostic Wells.
3 - Axis Geophones	3 Canisters Located Above the Coal Seam in 1 Diagnostic Well.
	Will Evaluate Microprocessor-Based Acquisition System.
<u>INDUCED SEISMIC</u>	
"State-of-the-Art," High Resolution Seismic Survey	Contracted Effort; Specifications Being Defined.

to Hanna II. Two additional objectives of the instrumentation effort include: (1) the development of a minicomputer-based data acquisition system to provide real-time, on-site reduction, analysis and display capabilities for all the instrumentation techniques, and (2) the development of a diagnostic well specification for in situ geo-energy applications and which will cover the hardware, fielding, data acquisition, and analysis aspects for the thermal and in-seam gas sampling and pressure instrumentation.

REFERENCES

1. D. A. Northrop and H. M. Stoller, "Feasibility Studies of Measurement Techniques Applied to In Situ Coal Gasification," Sandia Laboratories Report, SAND75-0028, March 1975.
2. Papers presented and published in the Proceedings of the 2nd Annual Underground Coal Gasification Symposium, Morgantown WV, August 10-13, 1976; Morgantown Energy Research Center, Report MERC/SP-76/3:
 - (a) C. F. Brandenburg, D. D. Fischer, D. A. Northrop, and L. A. Schrider, "Results and Status of the Second Hanna In Situ Coal Gasification Experiment." (p. 36)
 - (b) D. D. Fischer, C. F. Brandenburg, S. B. King, R. M. Boyd, and H. L. Hutchinson, "Status of the Linked Vertical Well Concept in Underground Coal Gasification." (p. 354)
 - (c) A. E. Humphrey, T. E. Sterner, H. L. Hutchinson, and G. G. Campbell, "Practical Considerations in Designing an Underground Coal Gasification Field Test." (P. 339)
 - (d) D. E. Eastwood, J. K. Eastlack, J. W. Jennings, S. B. King, W. J. Lanum, and D. F. Moore, "Real-Time Process Monitoring in Underground Coal Gasification," (p. 226)
 - (e) D. D. Fischer, "Monitoring of Emissions from an In Situ Coal Gasification Experiment." (p. 242)
3. Booz-Allen Applied Research, "ERDA's Underground Coal Gasification Program," ERDA Overview Report, ERDA 77-51/4, March 1977. Also "The Laramie Energy Research Center's Underground Coal Gasification Program, May-June 1977," an informal report available from LERC, Laramie Wyoming, 82071.
4. C. F. Brandenburg, R. P. Reed, R. M. Boyd, D. A. Northrop and J. W. Jennings, "Interpretation of Chemical and Physical Measurements from an In Situ Coal Gasification Experiment," SPE Paper 5654 presented at the 50th Annual Fall Meeting of the Society of Petroleum Engineers of AIME, Dallas TX, September 28 - October 1, 1975.

5. D. A. Northrop (Editor) "Instrumentation and Process Control Development for In Situ Coal Gasification: Fifth Quarterly Report, December 1975 through February 1976," Sandia Laboratories Report, SAND76-0191, April 1976.
6. R. L. Powell, "Thermocouple Reference Tables Based on the IPTS-68," NBS Monograph 125, National Bureau of Standards, Washington DC, 1974.
7. R. P. Reed, "Branched Thermocouple Circuits in Underground Coal Gasification Experiments," Proceedings of the 22nd ISA International Instrumentation Symposium, San Diego CA, May 25-27, 1976.
8. R. P. Reed, "The Transient Response of Embedded Thin Film Temperature Sensors," Temperature, Its Measurement and Control in Science and Industry, Instrument Society of America, Volume 4, Part 3, Page 2193, Pittsburgh PA, 1972.
9. S. G. Beard and R. P. Reed, "Some Observations from Temperature Measurements on Recent Underground Coal Gasification Experiments," Proceedings of the Second Annual Underground Coal Gasification Symposium, Morgantown WV, August 10-13, 1976; Morgantown Energy Research Center, Report MERC/SP-76/3, 1976.
10. P. J. Hommert and S. G. Beard, "Descriptions of Reverse Combustion Linkage and Forward Gasification During Underground Coal Gasification," 2nd Joint CIC-ACS Conference, Montreal Canada, May 29 - June 2, 1977. American Chemical Society Preprints, Division of Fuel Chemistry, 22 (4) 76-86, 1977.
11. P. J. Hommert, S. G. Beard and R. P. Reed, "Thermal Instrumentation and Data Analysis for Underground Coal Gasification," Proceedings of the 3rd Annual Underground Coal Conversion Symposium, Fallen Leaf Lake CA, June 6-10, 1977; Lawrence Livermore Laboratory Report, to be published.
12. J. W. Jennings, R. D. Gunn, C. F. Brandenburg, and D. L. Whitman, "The Areal Sweep Efficiency of the In Situ Recovery of Subbituminous Coal," SPE 6181 presented at the 51st Annual Fall Meeting of the Society of Petroleum Engineers of AIME, New Orleans LA, October 3-6, 1976.
13. D. A. Northrop (Editor), "Instrumentation and Process Control Development for In Situ Coal Gasification: Second Quarterly Report, March through May 1975," Sandia Laboratories Report, SAND75-0366, June 1975.
14. G. V. Keller and F. C. Frischknecht, Electrical Methods in Geophysical Prospecting, Pergamon Press, New York NY, 1966, pp. 90-196.

15. D. S. Parasnis, Mining Geophysics (2nd Edition), Elsevier Scientific Publishing Company, New York NY, 1973, pp. 195-201.
16. L. C. Bartel, "Model Calculations of Electric Fields Measured with a Fixed Stationary Array to Monitor In Situ Coal Gasification," Sandia Laboratories Report, SAND76-0076, February 1976.
17. L. C. Bartel, to be published.
18. W. Blake, F. Leighton, and W. I. Duval, "Microseismic Techniques for Monitoring the Behavior of Rock Structures," U.S. Bureau of Mines Bulletin 665, 1974.
19. W. Blake, "Rock Burst Research at the Galena Mines," U.S. Bureau of Mines Technical Progress Review TPR 39, August 1971.
20. N. G. W. Cook, "The Application of Seismic Techniques to Problems in Rock Mechanics," Int. J. Rock Mech. Mining Sci., 1, 169-179 (1964).
21. L. W. Beckham, "Analysis of Passive Acoustic Signals Generated by an In Situ Coal Gasification Process," Sandia Laboratories Report, SAND76-0124, March 1976.
22. L. C. Bartel, L. W. Beckham, H. D. Garbin, and R. W. Seavey, "Electrical and Seismic-Acoustic Results from the Second Hanna In Situ Coal Gasification Experiment," Proceedings of the 3rd Annual Underground Coal Conversion Symposium, Fallen Leaf CA, June 6-10, 1977. Lawrence Livermore Laboratory Report, to be published.
23. L. W. Beckham, "Estimating the Extent of an In Situ Coal Gasification Process Using a Passive Seismic Technique," Sandia Laboratories Report, to be published.
24. J. P. Eaton, "HYPOLAYR, A Computer Program for Determining Hypocenters of Local Earthquakes in an Earth Consisting of Uniform Flat Layers Over a Half Space," U.S. Geological Survey, Open File Report, June 1969.
25. N. T. Gaardner, "On Estimating the Location of a Signal Source," IEEE Trans. on Information Theory, 11-15 (5) 570-576 (1969).

26. L. W. Beckham and H. D. Garbin, "Borehole-Borehole Seismic Studies of an In Situ Coal Gasification Process," Sandia Laboratories Report, to be published.
27. 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.
28. D. A. Northrop (Editor), "Instrumentation and Process Control Development for In Situ Coal Gasification: Sixth Quarterly Report, March through May 1976," Sandia Laboratories Report, SAND76-0362, July 1976.
29. J. B. Farr and R. C. Shopland, "High Resolution Seismic Profiling," Proceedings of the 3rd Annual Underground Coal Conversion Symposium, Fallen Leaf Lake CA, June 6-10, 1977, Lawrence Livermore Laboratory Report to be published.

PROGRAM BIBLIOGRAPHY

Sandia Laboratories Reports (Available NTIS)

1. D. A. Northrop, "Instrumentation Systems Development for In Situ Processing," Sandia Laboratories Report, SAND73-0919, Sept. 1973.
2. D. A. Northrop, H. M. Stoller, "Feasibility Studies of Measurement Techniques Applied to In Situ Coal Gasification," Sandia Laboratories Report, SAND75-0028, March 1975.
3. R. P. Reed, R. W. Morris, O. J. Birdsong, "Temperature Instrumentation for the Hanna Research Site Well 16 of the Laramie Energy Research Center In Situ Coal Gasification Project," Sandia Laboratories Report, SAND74-0394, July 1975.
4. H. M. Stoller, "In Situ Instrumentation Applied to Underground Coal Gasification," Sandia Laboratories Report, SAND75-0459, Sept. 1975.
5. S. D. Stearns, "Attenuation of Acoustic Compressional Waves in Coal and Shale at Hanna, Wyoming," Sandia Laboratories Report, SAND75-0471, Nov. 1975.
6. L. C. Bartel, "Model Calculations of Electric Fields Measured with a Fixed Stationary Array to Monitor In Situ Coal Gasification," Sandia Laboratories Report, SAND76-0076, February 1976.
7. L. W. Beckham, "Analysis of Passive Acoustic Signals Generated by an In Situ Coal Gasification Process," Sandia Laboratories Report, SAND76-0124, March 1976.
8. J. L. Dossey, "Underground Coal Gasification Technology in the USSR," Sandia Laboratories Report, SAND76-0380, July 1976.
9. H. M. Stoller, L. A. Schrider, and D. A. Northrop, "The Status of Instrumentation and Process Control Techniques for In Situ Coal Gasification," Sandia Laboratories Report, SAND76-0383, July 1976.
10. L. W. Beckham, L. C. Bartel, and R. W. Seavey, "Remote Monitoring of an In Situ Coal Gasification Process," Sandia Laboratories Report, SAND76-0417, August, 1976.
11. S. G. Beard and R. P. Reed, "Some Observations from Temperature Measurements on Recent Underground Coal Gasification Experiments," Sandia Laboratories Report, SAND76-0418.
12. L. W. Beckham, "Adaptive Processing of Seismic Signals in Noise for Improved Time of Arrival and Amplitude Estimates," Sandia Laboratories Report, SAND76-0553, October, 1976.

Program Quarterly Reports (Available NTIS)

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.

Eighth Quarterly Report, September through November 1976, Sandia Laboratories Report, SAND77-0251, February 1977.

Ninth Quarterly Report, December 1976 through February 1977, Sandia Laboratories Report, SAND77-0669, April 1977.

Presentations, Symposium Proceedings, Other Publications

1. D. A. Northrop, "In Situ Coal Gasification," IEEE Spring Symposium on Energy Research in New Mexico, Albuquerque, New Mexico, April 17-18, 1975.
2. H. M. Stoller, "In Situ Instrumentation Applied to Underground Coal Gasification," First Annual Underground Coal Gasification Symposium, July 28-August 1, 1975, Centennial, Wyoming.
3. C. F. Brandenburg (LERC), R. P. Reed (Sandia), R. M. Boyd (LERC), D. A. Northrop (Sandia), and J. W. Jennings (U. of Wyoming, LERC), "Interpretation of Chemical and Physical Measurements from an In Situ Coal Gasification Experiment," presented by C. F. Brandenburg at the 50th Annual Fall Meeting of the Society of Petroleum Engineers of AIME, September 28-October 1, 1975, Dallas, TX. Presentation published as SPE 5654.
4. R. P. Reed, "Diagnostic Measurements for Field Research on In Situ Energy Conversion," presented at the Winter Meeting of the American Nuclear Society, San Francisco, CA, November 16-21, 1975. Extended abstract published in the Transactions of the American Nuclear Society 22, 5, 1975.
5. H. M. Stoller, "Fossil Energy R&D at Sandia Laboratories," Sandia Laboratories Colloquium Series, Albuquerque, New Mexico, November 19, 1975 and Livermore, CA, December 9, 1975.

6. D. A. Northrop, "Instrumentation and Process Control Development for In Situ Coal Gasification," Sandia Laboratories Colloquium Series, Albuquerque, New Mexico, February 4, 1976.
7. L. C. Bartel, "Model Calculations of the Resistivity as a Result of the Reaction Zone in an In Situ Coal Gasification Experiment," Society of Exploration Geophysicists 29th Annual Midwestern Exploration Meeting, Dallas, TX, March 7-9, 1976.
8. H. M. Stoller, L. A. Schrider (LERC), and D. A. Northrop, "The Status of Instrumentation and Process Control Techniques for In Situ Coal Gasification," presented by H. M. Stoller at the 22nd ISA International Instrumentation Symposium, San Diego, CA, May 25-27, 1976. Paper will be published in the proceedings of the symposium.
9. R. P. Reed, "Branched Thermocouple Circuits in Underground Coal Gasification Experiments," The 22nd ISA International Instrumentation Symposium, San Diego, CA, May 25-27, 1976. Paper will be published in the proceedings of the symposium.
10. S. G. Beard and R. P. Reed, "Some Observations from Temperature Measurements on Recent Underground Coal Gasification Experiment," presented by S. G. Beard at the 2nd Annual Underground Coal Gasification Symposium, Morgantown, WV, August 10-13, 1976. Paper published in the proceedings as MERC/SP-76/3, p. 328.
11. L. W. Beckham, L. C. Bartel, and R. W. Seavey, "Remote Monitoring of an In Situ Coal Gasification Process," presented by L. W. Beckham at the 2nd Annual Underground Coal Gasification Symposium, Morgantown, WV, August 10-13, 1976. Paper published in the proceedings as MERC/SP-76/3, p. 214.
12. R. E. D. Stewart, "Utilization of Low Btu Gas From In Situ Coal Gasification for On-Site Power Generation," presented by D. A. Northrop at the 2nd Annual Underground Coal Gasification Symposium, Morgantown, WV, August 10-13, 1976. Paper published in the proceedings as MERC/SP-76/3, p. 372.
13. C. F. Brandenburg (LERC), D. D. Fischer (LERC), D. A. Northrop, and L. A. Schrider (MERC), "Results and Status of the Second Hanna In Situ Coal Gasification Experiment," presented by C. F. Brandenburg and D. A. Northrop at the 2nd Annual Underground Coal Gasification Symposium, Morgantown, WV, August 10-13, 1976. Paper published in the proceedings as MERC/SP-76-3, p. 36.
14. D. A. Northrop, "Field Instrumentation for In Situ Coal Gasification," short course in In Situ Technology - Coal, Chemical Engineering Department, University of New Mexico, Albuquerque, NM on July 15-16, 1976.
15. J. L. Dossey, "Chronological Review of the Russian In Situ Coal Gasification Technology," short course in In Situ Technology - Coal, Chemical Engineering Department, University of New Mexico, Albuquerque, NM on July 15-16, 1976.
16. 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. Presentation was published as SPE 6151.

17. 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.
18. H. M. Stoller, C. F. Brandenburg (LERC), and D. A. Northrop, "An Assessment of In Situ Coal Gasification," presented by H. M. Stoller at the Spring Topical Meeting of the American Nuclear Society, Golden, CO, April 12-14, 1977. Paper will be published in the proceedings of the meeting.
19. P. J. Hommert and S. G. Beard, "Descriptions of Reverse Combustion Linkage and Forward Gasification During Underground Coal Gasification," presented by S. G. Beard at the 2nd Joint Chemical Institute of Canada/American Chemical Society Conference, Montreal, Canada, May 30 - June 2, 1977. Paper published in the proceedings at the Division of Fuel Chemistry, American Chemical Society, 22 (4) p. 76-86, 1977.
20. P. J. Hommert, S. G. Beard, and R. P. Reed, "Thermal Instrumentation and Data Analysis for Underground Coal Gasification," presented by P. J. Hommert at the 3rd Annual Underground Coal Conversion Symposium, Fallen Leaf Lake, CA, June 6-10, 1977. Paper to be published in the proceedings.
21. L. C. Bartel, L. W. Beckham, H. D. Garbin, and R. W. Seavey, "Electrical and Seismic Acoustic Results from the Second Hanna In Situ Coal Gasification Experiment," presented by L. C. Bartel at the 3rd Annual Underground Coal Conversion Symposium, Fallen Leaf Lake, CA, June 6-10, 1977. Paper to be published in the proceedings.
22. D. A. Northrop, "Sandia Laboratories Project Review: Instrumentation and Process Control Development for In Situ Coal Gasification," 3rd Annual Underground Coal Conversion Symposium, Fallen Leaf Lake, CA, June 6-10, 1977. Summary to be published in the proceedings.
23. D. D. Fischer (LERC) and D. A. Northrop, "A Description and Overview of the Hanna Wyoming In Situ Coal Gasification Project," presented by Fischer and Northrop at the 3rd Annual In Situ Energy Recovery Technology Short Course, Chemical Engineering Department, University of New Mexico, Albuquerque, NM, July 11, 12, 1977.

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