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INSTRUMENTATION AND PROCESS CONTROL
DEVELOPMENT FOR IN SITU COAL GASIFICATION
NINTH QUARTERLY REPORT:
DECEMBER 1976 THROUGH FEBRUARY 1977

DAVID A. NORTHROP, EDITOR

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INSTRUMENTATION AND PROCESS CONTROL DEVELOPMENT
FOR IN SITU COAL GASIFICATION

Ninth Quarterly Report: December 1976 through February 1977

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HIGHLIGHTS

Plans for the instrumentation effort associated with the Hanna IV experiment are nearly completed. Thirty diagnostic wells and surface probe arrays will be used for the eight techniques (thermal; in-seam gas sampling and pressure, subsidence, passive acoustic, two remote electrical methods, and a high-resolution seismic survey) to be fielded. Fielding is scheduled for spring and summer with test initiation in September 1977 (p. 5).

Thermal data from Hanna II have been validated based upon resistance and circuit noise measurements (p. 7). These data have been analyzed to provide detailed characterization of the thermal gradients, combustion front profiles and local gas fluxes during gasification (p. 10). A modular thermocouple design for general in situ applications has been defined and will be evaluated on Hanna IV (p. 14).

A well-to-well induced seismic technique was able to detect the progression of the process during Hanna II. An assessment of this technique is underway and the causes of changes in time-of-arrival and amplitude of induced signals have been determined (p. 16).

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Previous quarterly reports for this program are:

Instrumentation and Process Control Development for In Situ Coal Gasification:

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

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

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

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

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

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

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

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

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I. INTRODUCTION

This is the ninth quarterly report for Sandia Laboratories' program on Instrumentation and Process Control Development for In Situ Coal Gasification. This report summarizes program activities between December 1, 1976 and February 28, 1977 which have been conducted primarily in conjunction with the Laramie Energy Research Center's (LERC) underground coal gasification program and field experiments being conducted near Hanna, Wyoming.

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

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

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

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

II. INSTRUMENTATION AND FIELDING SUMMARY (D. A. Northrop, 5732 and J. A. Beyeler, 1125)

The Second Hanna Experiment has been completed. Phase 1, a site characterization and preliminary gasification test, was conducted between January and August, 1975. Phases 2 and 3, the major parts of the experiment, were fielded between August and November, 1975 and were conducted between April and July, 1976. Detailed descriptions of all aspects, results, and initial interpretations of the recent phases can be found in a series of papers which will appear in the Proceedings of the 2nd Underground Coal Gasification Symposium, Morgantown WV, August 1976.

Sandia's major instrumentation effort was associated with Phases 2 and 3 of the Second Hanna Experiment. Instrument fielding details and specific sensor locations were given in the Fourth Quarterly Report (p. 8-17). A summary of the instrumentation and well locations are presented for reference in Table I and Figure 1; dated activity summaries appeared in the Eighth Quarterly Report (p. 7).

Plans are being finalized and work has been initiated for Sandia's instrumentation effort in conjunction with the Hanna IV in situ coal gasification experiment to be conducted in late 1977. (Hanna III will be a limited gasification test with specific environmental objectives to be conducted by LERC during 1977.) As before, both diagnostic and remote monitoring instrumentation techniques will be fielded utilizing both instrumentation wells within the experimental area and surface probe arrays. The diagnostic techniques include: temperature measurements via branched thermocouple circuitry which allows for redundancy and data validation, gas canisters and sampling lines providing access to in-seam gas samples and pressure measurements, and a feasibility test of a time domain reflectometry or slifer-based method to measure the vertical progress of subsidence from the seam towards the surface. Based upon assessment of Hanna II results, development of the following remote monitoring techniques will continue and will be evaluated on the Hanna IV test: (a) both the direct excitation electrical potential (DEEP) and modified Schlumberger (MS) current configurations will be used with a large surface probe array and a probe in each diagnostic well above the coal seam and (b) passive acoustic source mapping by geophone assemblies located in the overburden in selected wells. The induced seismic technique will be pursued via a contracted, high-resolution geophysical seismic survey. All instrumentation techniques will use a central minicomputer-based data acquisition system for on-site processing, reduction and display. The development and implementation of this system is one objective of the field effort.

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

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

- NOTES: (1) UP TO SIX-FOLD REDUNDANCY AT MOST LEVELS PLUS RESISTANCE AND NOISE MEASUREMENTS GREATLY INCREASE THE TOTAL NUMBER OF THERMAL CHANNELS AVAILABLE.
- (2) DIFFERENT MATERIALS FIELDIED FOR EVALUATION.
- (3) THREE PROBES ALSO FIELDIED IN SHOT-WELL, S1.
- (4) HIGH TEMPERATURE SENSORS AND CABLES FIELDIED IN THESE WELLS.
- (5) DIFFERENT GEOPHONE SPACING TO MEASURE VERTICAL ATTENUATION.

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

30 diagnostic instrumentation wells containing thermocouples and gas sampling canisters are currently planned. The well pattern is nearing final definition. Well locations are being determined by a methodology under development for the optimum placement of given number of wells, each with effective 7-10 ft radius, to maximize the information and temporal coverage for a test of large areal extent. Relative to Hanna II, Hanna IV will have twice the number of instrumentation wells to cover approximately eight times the area.

Field activities are scheduled to begin April 1, 1977. A four month fielding effort is anticipated with test initiation scheduled for September 1977.

III. TEMPERATURE STUDIES

A. Hanna II Thermal Data (S. G. Beard - 5732, R. P. Reed - 1116, P. J. Hommert - 5732)

Processing of the thermal data recorded at intervals of 15 minutes to one hour during Phases 2 and 3 of the Hanna II experiment is almost complete. The reduction of these data was seriously delayed by difficulties encountered in reading some of the magnetic tapes written by unreliable data loggers and recorders at the test site. The validation and analysis of these data is underway and an example of the type of thermal analysis possible with the 15-minute data is discussed in the following section.

Data validation involves determining which data are reliable by qualitative examination of the temperature plots and analysis of available noise emf and thermocouple circuit resistance data recorded during the test. Examples of the resistance data for some thermocouple circuits are presented in Figure 2, and typical plots of temperatures and circuit resistances are shown in Figures 3 and 4. The temperature data presented in earlier quarterly progress reports indicated that, in general, the maximum temperatures in all wells (except Wells K and N) ranged from 1000°F to 2000°F.

Resistance changes of a few ohms can result from heating of the thermocouple wire. However, when resistance changes greater than these ranges are measured, the validity of the temperature data is questionable. Fluctuations in the resistance and decreases such as those in Well F in Figure 2 can result from noise emf in the thermocouple circuit; superposition of this noise on the thermoelectric emf would invalidate the temperature measurement made with this circuit. In other cases, the circuit resistance returns to its previous value; this may indicate that the junction has to be reformed at a higher level resulting in "valid" temperatures, but at an unknown location.

Figure 2. Examples of thermocouple circuit resistances measured during the Hanna II UCG experiment for well and level indicated.

Comparisons of temperature and resistance data indicate significant changes in resistance are often associated with rapidly oscillating temperatures which can fluctuate more than 1000°F between scans. Examples of this type are shown in Figure 4 where the onset of invalid temperature data is fairly obvious. (The maximum validated in situ temperature found in the examination of the 15 minute data was approximately 1900°F at the 5-foot level in Well G just 3 hours before the beginning of spurious data.)

The diagnostic data is especially useful in establishing the validity of the temperature responses which are suspect but not as obviously invalid as the appearance of "negative" temperatures. Examples of this type are seen in Figures 3 and 4 where temperature decreases were observed following rapid rises in temperature from 120-200°F to 800-1300°F. The validation and accurate interpretation of these

Figure 3. Temperatures and thermocouple circuit resistances for the 10-foot level in Well C during Hanna II, Phase 2. (Both entire record and expanded record in period of interest given.)

Figure 4. Temperatures and thermocouples circuit resistances for the 10-foot level in Well F and 5-foot level in Well G during Hanna II, Phase 2.

data are critical because location and rate of movement of the gasification zone boundary may be defined by these temperature responses and are important in process model development. For example, if 1500°F has been defined as the gasification temperature, the data in Figure 3 would indicate that gasification occurred at this location on Day 136 whereas the resistance data suggests that the temperature decrease to 600°F on Day 134 and the subsequent increase to over 2000°F on Day 136 are questionable. An example of a valid temperature decrease following rapid increase (Day 127.5) is seen in the Well F, 10-foot data. Later (Day 130.2), the data become suspect, and it is not clear when or if the temperature increased to 1500°F at these locations.

During the Hanna IV test every temperature measurement will be accompanied by measurements of one or more associated diagnostics. The experience in analyzing the Hanna II temperature data, and especially in interpreting the data during periods of rapid heating with only a limited amount of diagnostic data, demonstrated the importance of this procedure. These measurements will be made with a Sandia-designed, computer-controlled, combinational multiplex (COMUX) switching system which has been designed to measure approximately 1000 quantities in the 30 instrumentation wells on each scan.

B. Thermal Data Analysis: Combustion Front Profiles (P. J. Hommert, 5732)

One of the most characteristic features of the thermal responses seen during the Hanna II test are the many rapid (< 1 day) temperature rises from near ambient to 1000°F and above. Under the assumption that many of these responses are associated with an advancing combustion front, detailed examination may provide information about the thermal structure of the front and be useful for comparison with analytical models of the in situ combustion process.

The choice of appropriate responses for examining the combustion front is narrowed by two considerations. First, the sensor should be one that responded during the period of most active forward gasification after Day 125 and was relatively unaffected by gas flow down the primary linkage path. Second, the sensor should be one located in the bottom portion of the seam to reduce the likelihood that the response is associated with a subsidence event. Based on these considerations, the responses shown in Figure 5 at the 5-foot level in Well C around Day 127.5 and the 10-ft level in Well A around Day 135.0 have been examined in detail. The curves are referenced to an arbitrary initial time prior to the onset of rapid heating. Data are from scans taken every 15 minutes.

Figure 5. Combustion front profiles based on scans every 15 minutes.

Figure 5 indicates the presence of a drying period whose length varies, as might be expected, with well location. The majority of the temperature rise occurs over a period of less than half a day, during which peak heating rates are on the order of $4.8 - 8.7^{\circ}\text{F}/\text{min}$ ($2.7 - 4.8^{\circ}\text{C}/\text{min}$). The apparent breaks in the curves around 1000°F are interesting since this is near the temperature of maximum rate of devolatilization and thus could be associated with a devolatilization endotherm. It must be recognized, however, that these breaks could also be due to effects within the grout column or the thermocouple strings themselves, but examination of the hourly loop resistance record for the 5-ft level in Well C shows no irregularities during this time period. It is difficult to make comparisons at higher temperatures ($> 1300^{\circ}\text{F}$) because of increasing distortion of the combustion field by the grout column, the possibility of unreliable thermocouple data and local fluctuations in the flow field.

The two curves of Figure 5 cannot be directly compared because these temporal records may have been caused by combustion fronts moving at different velocities. To eliminate this effect, the temperature-versus-time histories can be converted to spatial profiles by assuming a combustion front velocity. Figure 6 shows spatial profiles obtained from the data of Figure 5 assuming velocities of 2 and 3 ft/day which are consistent with the general velocity trends indicated by the thermal data. This figure indicates the steep temperature gradients seen in the in situ process; between 400 and 900°F , the temperature gradient is on the order of $250\text{--}500^{\circ}\text{F}/\text{in}$. The spatial profiles still indicate a different structure at the two locations resulting from variations in local conditions within the seam. It should be noted, however, that in the temperature range from 400 to 900°F , the gradients indicated by the 3 ft/day curve in Well A and 2 ft/day curve in Well C are nearly identical.

Figure 6. Spatial profile resolved from temporal data using assumed front velocities. (Curves truncated at 1300°F.)

The data between 400 and 900°F in Figure 5 can be used to estimate the local gas flux by examining the energy equation for the one-dimensional case which can be written as

$$\rho_c \bar{C}_p \frac{\partial T}{\partial t} = \rho_g C_{pg} V_g \frac{\partial T}{\partial x} + \frac{\partial}{\partial x} \left(k_c \frac{\partial T}{\partial x} \right) \quad (1)$$

where

- ρ_c = coal density
- ρ_g = gas density
- C_p = effective coal specific heat
- C_{pg} = gas specific heat
- k_c = coal thermal conductivity
- V_g = gas velocity.

Writing the equation in this form implies a number of assumptions. First, chemical reactions, outside of those associated with devolatilization, do not contribute significantly to the energy balance in this temperature regime. Second, the gas and solid are at the same temperature and the heat capacity of the gas is negligible when compared to that of the solid. The endothermic effects of devolatilization are accounted for by defining an effective coal heat capacity as a function of temperature according to the function given by Gunn and Whitman.* In order to correlate Equation 1 with the data of Figure 5 it is necessary to assume a constant combustion front velocity V_f . Equation 1 can then be rewritten as an expression for the gas velocity as

$$V_g = \frac{\rho_c \bar{C}_p \frac{\partial T}{\partial t} - \frac{1}{V_f} \frac{\partial}{\partial t} \left(k_c \frac{\partial T}{\partial t} \right)}{\frac{\rho_g C_{pg}}{V_f} \frac{\partial T}{\partial t}} \quad (2)$$

Numerical estimates of the time derivatives can then be used in Equation 2 to estimate the local gas velocity for an assumed combustion front velocity. Figure 7 summarizes the results of the analysis by plotting calculated gas flux (adjusted to standard conditions) versus the assumed combustion front velocity. Results are presented at two different temperatures along the profile from the 5-ft level in Well C. These curves should not be interpreted as providing a relationship between gas flux and combustion front velocity but rather as indicating the range in the results introduced by uncertainty in the front velocity. Also, it should be recognized that this analysis is based on a one-dimensional approximation that neglects the multi-dimensional effects on the flow field induced by changes in the coal as it is heated such as the removal of water. Obviously the effect of uncertainty in front velocity is such that Figure 7 can only be used to provide an estimate of the gas flux. The higher fluxes at the lower

Figure 7. Estimated gas fluxes near the combustion zone as function of assumed front velocities.

*Gunn, R. D. and Whitman, D. L., "An In-Situ Coal Gasification Model (Forward Mode) for Feasibility Studies and Design," Rept. LERC/R1-76/2, Laramie Energy Research Center, Laramie Wyoming, Feb. 1976.

temperature may result from increased flow of pyrolysis products at that point. The indicated flux values are not inconsistent with what might be expected for regions of coal near the void area when overall dry gas production rates are in the range of 4-6 MM scf/day.

C. Hanna IV Thermal Instrumentation (R. P. Reed - 1116, S. G. Beard - 5732, P. J. Hommert - 5732)

As part of the development of a diagnostic well for use in geo-energy experiments, the design of multipoint thermocouple assemblies has been generalized and standardized to simplify procurement and to reduce cost and fabrication time. Modular 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 total number of wells or their specific locations. As experiment plans are made definite, only a few elements of additional information are then required to finalize the instrumentation design.

A modular in situ thermocouple assembly is shown in the sketch in Figure 8. Details of some of the specifications and options available to the experimenter or designer are also listed in the figure. Similar thermocouple assemblies have been utilized to successfully measure in situ temperatures in the previous Hanna experiments.

Detailed design specifications for the Hanna IV temperature measurement system have been completed, and orders for the fabrication of the thermocouple assemblies have been placed. Testing of some of the system components has also been performed. Six, leg-branched Chromel-Alumel thermocouples, insulated with magnesia and sheathed with 0.125-inch O.D. Inconel 600 alloy, will be installed and grouted in each thermal instrumentation well. The leg-branched thermocouples will allow redundant temperature measurements at 12 locations and also the measurement of diagnostic quantities such as temperature differences, circuit resistances and noise emf. The two junctions in each leg-branched thermocouple will be located 10 feet apart, and the six, leg-branched thermocouples will be positioned so that temperatures are measured every 3.33 feet from the seam floor to 6.66 feet above the seam ceiling. The metal-sheathed thermoelectric elements will extend 20 feet above the top of the seam to a canister where the 12 pairs of wires will be spliced to thermocouple extension wire. The temperature in this canister will be measured with a thermistor. Aluminum-shielded, 16-pair thermocouple extension cable will extend from the canister to a surface junction box and then to the recording trailer.

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,
W5%Re/W26%Re, Pt/Pt10%Rh
3. Sheath: Stainless Steel, Inconel,
Hastelloy, Tantalum
4. Insulation: MgO, BeO
5. Temperature: ≤ 2000 F
6. Sensor Spacing, A: 1.3, 2.5, 3.3,
5, or 10 ft.

INSTRUMENT WELL

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

Figure 8. Modular in situ thermocouple assembly.

IV. SEISMIC-ACOUSTIC STUDIES

A. Passive Acoustic Experiment (L. W. Beckham, 5732)

The activity of acoustic events during Phase 3 has been determined and is shown in Figure 9. As before, activity is primarily associated with periods of gasification. Comparison with Phase 2b activity indicates that acoustic emission during Phase 3 was much more frequent and, in general, higher signal-to-noise ratios were observed.

The locations of 17 events during Phase 2b have been determined. A plot of the relative frequency of these events in the plan view is presented in Figure 10. A total of 170 events have been digitized and placed on magnetic tape. These events will be filtered, their times of arrival estimated and locations determined, and amplitude statistics will be found.

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

Induced seismic data obtained during Phase 2b pretest (Day 85), linkage (Day 125), and gasification (Days 132, 139, and 146) periods are being analyzed by two techniques. First, times-of-arrival (TOA) and first peak amplitudes for signals observed pretest and during the test are compared to see if outlines of the process can be delineated by a

Figure 9. Frequency of passive acoustic activity, Phase 3.

Figure 10. Relative frequency of passive acoustic events. (The cell size is 5 x 5 ft.)

"shadowing" model. Second, a detailed reflection analysis (given in the Seventh Quarterly Report, page 26) provides additional information on the vertical growth of the reaction.

Examples of the induced seismic records are shown in Figure 11. Records in this format are useful for visual interpretation but do not allow for accurate TOA or amplitude evaluation; a computer code operating on the digitized records provide this function. Pretest records indicate which channels are bad and indicate the normal spreading of the signal arrivals for detonator #1 (the lowest, 40 ft below the coal seam). Data midway in Phase 2b show that several geophones have been burned out

and modifications of signal character are obvious throughout. Near the end of Phase 2b, the effects of shadowing of detonator #1 by the process are very pronounced. Most of the surviving channels present shadowed records with the highest channels in Well D being the least affected. There are also several examples of apparently shorted channels where neighboring records are identical (e.g., Well A, levels -20, -10, 0, and 7.5).

Amplitude data are difficult to work with after Day 132 and TOA data appear most sensitive to the process. Comparisons of TOA for Days 139-132 and 146-139 provide an interpretation of the extent of the process. Because of the destruction of the layering symmetry, the reflection analysis was carried out on the time plots as well as signal spectra. The results of the analysis for Day 139 and plan view results for Days 132, 139, and 146 are presented in Figures 12 and 13, respectively. "Minimum boundary" is defined as the edge of the process closest to the 5-6 line and corresponds to the intersection of the shadowing and reflection boundaries. The actual maximum extent of the process for all three days cannot be determined except to note that a gas leak into Well S1 occurred on Day 148.

An assessment of the induced seismic technique is being made based on these analyses. The basis for the techniques is found in the following observations:

- a) Time of arrival changes are related to several major mechanisms: (1) drying out of natural fractures in area resulting in a 2-4% velocity change,

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

Figure 11. 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.)

Figure 12. Two-dimensional profiles for the shadowing and reflection analyses on Day 139.

Figure 13. Minimum boundary of affected coal found by the induced seismic technique.

(2) an edge effect around the gasification zone which amounts to a 0.3 - 0.5 ms change in arrival times along these paths, (3) a void effect for waves that follow the boundary of the gasification zone which produces TOA changes of 1-3 ms and (4) an error of 0.1 - 0.2 ms due to inaccurate estimates of the arrival time of a signal in noise.

b) Amplitude effects are due to the following: (1) variations in detonator strength, (2) noise in the channels, and (3) diffraction of seismic waves around void.

The assessment will be defined further in a report being written on this technique.

V. ELECTRICAL STUDIES

A. Analytical Capability Development (L. C. Bartel; 5732)

The analytical capability development for interpreting and quantifying the electrical data for both the modified Schlumberger (MS) and direct excitation electrical potential (DEEP) techniques is continuing. At the present time, attention is being focused on the analysis of the DEEP data. Two general approaches for the mapping and characterizing the reaction zone are being taken: (a) a least squares fitting procedure and (b) a linear inverse mapping technique. Most of this quarter's attention was focused on the latter.

A least squares fitting procedure, discussed in the Eighth Quarterly Report, is being investigated to fit model parameters (size, shape, and location of the reaction zone) to experimental DEEP data. The least squares program under investigation is based on a modification of the Levenberg-Marquart algorithm. Preliminary calculations indicate that the results are sensitive to the current distribution on the well casings and to the location of the center and the surface area of the reaction zone. This technique will be investigated further.

The potential measured at the surface is due to the currents emitted from the current wells (positive and negative) and the hot conducting reaction zone. The positive electrode is taken to be a process well (or wells) along with the reaction zone. The potential due to a current distribution is given by

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

where ρ is the resistivity of the earth (assumed to be uniform for convenience), $j(\vec{x}')$ is the current density distribution normal to the surface S , and $G(\vec{x}, \vec{x}')$ is the half-space Green's function given by

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

The linear inverse analysis to map the reaction zone consists of using surface potential data to determine the current densities on grid planes chosen to simulate the actual reaction zone current source. The potential at point i due to the current well sources and the reaction zone is given by

$$\phi_i = \rho \sum_{\ell} A_{\ell} G(i, \ell) j_{\ell}, \quad (5)$$

which can be written in matrix notation simply as

$$A X = B. \quad (6)$$

Equation 5 or 6 represents a system of linear algebraic equations to be solved for the current density distribution, j_{ℓ} in (5) or X in (6). From the non-zero current density distribution, the shape, size and location of the reaction zone can be determined.

The system of equations is too ill-conditioned to be solved by conventional methods. The ill-conditioning is a result of the nearly equal distances from all current grid points to all observation points (i.e., all $G(i, \ell)$'s are nearly equal for all i and ℓ). To solve the system of equations for the current densities a non-negative linear least squares algorithm* is used with the constraint that the sum of the current densities times the appropriate area equals the total current injected:

$$I = \sum_{\ell} A_{\ell} j_{\ell}. \quad (7)$$

This system of equations can be overdetermined (more equations than unknowns) to give more accurate results by increasing the number of probes (i.e., data points) in the surface array.

* C. L. Lawson and R. J. Hanson, Solving Least Squares Problems, (Prentice-Hall, Inc., Englewood Cliffs, NJ, 1974), pp 160-165, 269-271.

To test the validity of the linear inverse technique to analyze DEEP data, calculated data were used to determine the simulated current source. Result of an illustrative calculation for an overdetermined system of equations is shown in Figure 14. Two horizontal current grid planes, one located beneath the other, are used and the depth and vertical separation between the planes is adjusted to give minimum in the residual. The actual calculated current source consists of the lower 89% of the production and injection well casings and a combustion zone current source of finite height (5 m) shown by the dashed lines. The solid lines are contour lines of equal current density as determined in the upper grid plane. For the minimum residual, the upper and lower grid planes are approximately at the depth of the top and the bottom of the current source, respectively. The region of high current density coincides with the actual current source as shown.

The results shown do not include the effects of errors that would be present in actual field data. With random errors introduced into the calculated potentials, the resulting current distributions show primarily the location of the center of the source and do not indicate the extent of the reaction zone. Additional work is needed in the analysis to be able to handle the introduction of errors into the data. Work has begun on an iterative improvement technique to be applied to the results obtained from the fitting procedure.

Figure 14. 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.

VI. TILT AND DISPLACEMENT MEASUREMENTS (D. A. Northrop, 5732)

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.

Failure of these techniques are 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. Table II 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.

Table II
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.

VII. DATA SYSTEMS DEVELOPMENT

A. Field Data Acquisition and Recording System (K. B. Kimball, 1125)

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

The minicomputer and its associated hardware have been purchased and are scheduled for shipment prior to April 1, 1977. Sandia-furnished portions are being fabricated. The system will be housed in 10 x 40 ft instrument trailer which has been redesigned and is being modified to meet the requirements of this system.

The only major component not on order is a 480 input pair multiplexer for the thermal acquisition subsystem; 320 input pair multiplexer is on hand and will be used initially. Studies of the thermal systems components have indicated satisfactory performance with acceptable thermal emf and noise characteristics. Still lower noise and power consumption could be obtained by the use of latching, instead of reed, relays.

Data loggers will be used for the back-up recording of thermal data. The present plan to attach the loggers in parallel will proceed with caution until results from laboratory tests are evaluated. There is reason to suspect, based upon limited Hanna II experience, that such parallel circuitry will not work with acceptable precision.

B. Software Development Activities (G. S. Davidson - 5732, H. C. Ogden - 1111, E. J. Young - 1125)

Software is being designed for the Hanna II field acquisition system with the objective that it be general and flexible to allow easy transfer to future experiments or different instrumentation techniques. The system being developed will allow field modification without reprogramming. Preliminary design of the thermal acquisition system as well as the development of various plotting packages for field data recovery have been completed this quarter. A contour package has been chosen and is being implemented.

To achieve greater flexibility, a "table-driven" design was chosen for the thermal acquisition system. All the details of a given experiment are contained on a set of computer cards which are filled out by the experimenter. The cards are processed into a internal table of parameters. The main acquisition program interprets these tables to determine the hardware states required to capture the measurement. The experiment can be modified at any time by changing the input cards to reflect the desired modification.

Physical limitations in storage available for the minicomputer precludes having all data accessible in the field. Hence some form of compression is required for the field files. A previous study (Sixth Quarterly Report, p. 39) indicated that storing only values that differ by a fixed percent from the previously stored value can save a great amount of storage as seen in Figure 15. For example, if those values which differ by at least one percent are recorded, the storage needed will be only thirteen percent of the space required to save all the measurements.

For the thermal system, a tape will be made of all the data in full precision for subsequent processing at Sandia. Two files will be available for field processing, a long-term history file and a small file of recent activity. They are to be compressed using significant changes of two and one percent, respectively.

Figure 15. The relation between the smallest changes considered significant and the storage required. This calculation is based upon representative thermal data from Hanna II, Phase 1 experiment, August 1975.

C. Passive Acoustic Instrumentation (T. M. Schultheis, 9421)

The passive acoustic instrumentation system includes twenty four vertical-axis and three triple-axis velocity geophones, each with downhole amplifiers. A front-end switch selects either the single-axis or the triple-axis geophone channels for recording. The signals will be processed by the universal multichannel signal processor (UMCSP) first defined in the Fifth Quarterly Report (p: 27). The downhole amplifier has been tested using both vertical-axis and triple-axis geophones to determine gain bandwidth, impedance loading, frequency response, and the

signal-to-noise ratio. Components to implement this amplifier system have been ordered.

Development of the UMOSP has proceeded in conjunction with other activities. A set of front-end cards have been received and are being evaluated. The design of a 24 channel programmable switch that will be able to connect the conversion equipment to test signals, vertical axis or triple axis geophones is under way. Several new devices were purchased to expand the LSI-11 microprocessor system including a floppy disk, ROM bootstrap, and an input/output interface card allowing direct access to memory. Design is progressing on the front-end interface to control the analog to digital sample rate, the time code translator, the front-end switch, and units which access data from the front-end memory. A serial line switch is being designed to control the interconnection of data paths between the terminal, the acoustic coupler, the microprocessor, and the central minicomputer of the field data acquisition system.

VIII. PUBLICATIONS, PRESENTATIONS AND BRIEFINGS

A. Publications

1. D. A. Northrop, Editor, "Instrumentation and Process Control Development for In Situ Coal Gasification: Eighth Quarterly Report - September through November, 1976," Sandia Laboratories Report, SAND77-0251, February 1977.

B. Presentations

None this quarter.

C. Briefings

1. David A. Northrop, program briefing for Dr. H. McCarthy and co-workers from Occidental Petroleum at Sandia Laboratories Albuquerque NM, December 16, 1976.
2. Program staff, program briefing for Mr. M. N. Palmer and Mr. Burl Davis, Gulf Science and Technology Company at Sandia Laboratories, Albuquerque NM, February 24, 1977.
3. David A. Northrop attended Management Working Group for In Situ Coal Gasification meetings on November 30 - December 1, 1976 at FE/ERDA Washington DC and February 17-18, 1977 at SAN/ERDA, Oakland CA.
4. L. C. Bartel and D. A. Northrop attended the Geology and Field Operations Working Group for In Situ Coal Gasification at Lawrence Livermore Laboratory, Livermore CA, February 16, 1977.

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