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INSTRUMENTATION AND PROCESS CONTROL DEVELOPMENT
FOR IN SITU COAL GASIFICATION
TWENTIETH QUARTERLY REPORT:
SEPTEMBER THROUGH NOVEMBER 1979

R. E. GLASS, EDITOR

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INSTRUMENTATION AND PROCESS CONTROL DEVELOPMENT
FOR IN SITU COAL GASIFICATION

Twentieth Quarterly Report:
September through November 1979

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ABSTRACT

The second phase of the Hanna IV in situ coal gasification test, Hanna IV-B, which was initiated on April 20, 1979, was completed on October 4, 1979. Sandia National Laboratories provided support by fielding and monitoring diagnostic and remote monitoring instrumentation techniques. During the final gasification stage, 765 tons of coal were reacted involving 17,000 cubic feet.

The Hoe Creek III experiment conducted by Lawrence Livermore Laboratories began on August 15, 1979, and was terminated on October 10, 1979. The purpose of the experiment was to test the drilled borehole linking concept. Sandia National Laboratories' involvement consisted of fielding and monitoring both an inverted thermocouple and a surface electrical resistivity network. The inverted thermocouple was successfully tested and provided thermal data from beneath the burn zone. A real time analysis procedure for the electrical resistivity technique was implemented at Hoe Creek III. Unfortunately, there was insufficient change in the data for this to have been a useful diagnostic. Efforts are continuing to identify the reason for this lack of response.

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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, SAND75-0353, 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, SAND-76-0362, 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.

Tenth and Eleventh Quarterly Reports, March through August 1977, Sandia Laboratories Report, SAND77-1821, December 1977.

Twelfth Quarterly Report, September through November 1977, Sandia Laboratories Report, SAND78-0253, April 1978.

Thirteenth Quarterly Report, December 1977 through February 1978, Sandia Laboratories Report, SAND78-1224, June 1978.

Fourteenth and Fifteenth Quarterly Reports, March through August 1978, Sandia Laboratories Report, SAND78-2311, December 1978.

Sixteenth Quarterly Report, September through November 1978, Sandia Laboratories Report, SAND79-0706, April 1979.

Seventeenth, Eighteenth and Nineteenth Quarterly Reports, December 1978 through August 1979, Sandia Laboratories Report, SAND79-2386.

I. INTRODUCTION AND SUMMARY

This report covers the twentieth quarter of Sandia National Laboratories program on Instrumentation and Process Control Development for In Situ Coal Gasification. This report summarizes program activities conducted between September 1, 1979, and November 31, 1979, in support of the DOE Underground Coal Gasification Program and field experiments.

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 resource geology and (b) positive process control to produce a product of consistent quality with efficient resource utilization. The absence of this technical understanding and the lack of positive process control have been the major contributing factors which have prevented widespread development of in situ coal gasification despite world-wide interest and investigation over the past hundred years. The Sandia program for Instrumentation and process Control Development directly addresses these factors.

The objectives of 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 in situ process in order to further its understanding, (3) to develop and evaluate remote (and thus more versatile and economical) monitoring techniques and establish their correlation with the process, (4) to develop analytical models for the purpose of process identification, instrumentation development, and design and process modeling, and (5) to develop a process control system utilizing remote monitoring techniques to optimize the recovery of energy by in situ coal gasification. Activities during this period contributing to these objectives will be described in this report.

A major instrumentation effort was fielded on the Hanna IV-B in situ coal gasification experiment which was initiated in April 1979 and continued into October 1979. During this second stage of gasification, analysis of the data showed the combustion front progressing along the previously formed links between 20 and 25 feet above the floor of the coal seam. The results of the thermocouple data and material balance calculations made it possible to estimate the affected region and to determine thermal losses.

Sandia National Laboratories also undertook an instrumentation effort at the Hoe Creek III test. An inverted thermocouple string with lateral

transmission device was fielded which allowed investigators to determine the extent to which coal below the burn zone was affected. Sandia National Laboratories also provided a COMUX system to enable use of thermal diagnostics.

Also incorporated at the Hoe Creek III test was a model for analyzing the surface electrical resistivity network data. Due to a highly conductive region between the surface and the combustion front, the data obtained at Hoe Creek III has not proved as useful as that analyzed for Hanna IV-A.

Although the analytical and experimental techniques discussed here were developed for use in the in situ coal program, the techniques apply to any underground combustion process. As such, results from this program 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. HANNA IV-B THERMAL DATA ANALYSIS (R. E. Glass, 4737)

Introduction

The period from September through November 1979 saw the completion of the Hanna IV-B in situ coal gasification experiment. The coal was reignited after modifications were made to the piping system and gasification progressed until September 19. After gasification was terminated, the surviving thermocouple wells continued to be monitored until October 4, 1979. The sequence of events is presented in Table 1, and a map of the well pattern is shown in Figure 1.

This gasification stage saw the activation of the link through Wells NN, DD, SS, and 7 which had seen little thermal response during the first stage. The link through Wells CC and RR remained active giving good sweep width in the coal seam above the 20 foot level where the initial links were established.

Data

During gasification, thermal responses were detected in Wells EE, RR, DD, NN, SS, BB, and TT. In all of the above wells except TT, thermocouple

Table 1

Event Log Highlights - Stage 2 Gasification

Julian Date	Event
245	High pressure air injected to dewater the coal seam
246	Ignition with injection in Well 8 and production from Well 7.
262	Injection halted.
277	Data monitoring halted.

Figure 1. Hanna IV-B Well Pattern

temperatures exceeded 1000 C. The response in Well DD is an example of successive pyrolysis and combustion of the coal above the original link. The sequence of thermocouple responses is given in Table 2. Note that there were responses high in the coal seam prior to the end of the combustion process. This implies heating of the overburden and increased water influx which may account for much of the energy lost underground.

Table 2

Succession of Events Well DD

<u>Level (ft)</u>	<u>Time of Pyrolysis (>425 C) (Day)</u>	<u>Time of Failure (Day)</u>
20.1	247.13	247.2
23.2	247.04	247.1
26.8	248.33	248.4
30.0	250.33	250.4
33.3	251.83	251.9
36.8	255.17	255.2

The flame front continued through Wells NN, SS, CC, and BB in a similar manner. Figure 2 shows the heating of successive layers in Well NN. A typical thermal response can be seen in Figure 3, which depicts the 23 foot level of Well NN. The primary thermal processes are (1) conduction from A to B, (2) conduction and convection from B to C, (3) pyrolysis from C to D and (4) exposure to hot product gasses from D to E.

During the first gasification stage, responses were seen along the link from Well 3 through Wells EE, RR, CC, and BB to Well 7. Responses in Wells CC and BB shortly after ignition in Well 8 indicated that this was still an active link. The thermocouples along the link through Wells NN and SS seen during reverse combustion continued to show minimal response until the combustion front reached Well NN. After Well NN was reached, responses in Well SS indicated the presence of an additional path for the hot product gasses. The sequence of events is given in Table 3. The time for thermocouple failure gives a reasonable approximation to the time of arrival of the combustion front.

Table 3

Thermal Response - Stage 2 Gasification

<u>Well</u>	<u>Level (Ft)</u>	<u>Thermocouple Failure (Day)</u>
DD	23	247.1
NN	19	247.8
CC	20	255.5
SS	23	257.6
BB	26	258.4

Figure 2. Thermal Response in Well NN to the Combustion Front

Figure 3. Well NN - 23.2 Foot Level. Thermal Response of the Thermocouple from Conduction (A-B) to Pyrolysis (C) to Fluctuating Hot Gases (D-E).

Material balance calculations showed 765 tons of coal affected involving 17,000 cubic feet. Figure 4 shows the total amount of coal affected as a function of time with the amount gasified and the amount of char produced.

Energy balance calculations give the distribution of the heat generated by the combustion of the coal. Underground thermal losses during the test were 17%. The entire distribution is given graphically in Figure 5.

After shutdown a cooling period was monitored for sixteen days. Typical responses are shown in Figure 6. Automatic monitoring was halted on day 277 after which trailer B-35 returned to Albuquerque, NM, after two years on the site. The thermocouples are now terminated at a surface junction box where temperatures can still be measured.

Figure 4. Total Coal Affected with Amount Gasified and Amount of Char Produced.

Figure 5. Distribution of the Heat of Combustion of the Coal.

Figure 6. Post Combustion Data Well BB

Conclusions

The second stage gasification at Hanna IV-B proceeded with the flame progressing along the formed links and coal collapsing in successively higher layers until the overburden was reached. The problem of low resource utilization was the result of the links being formed between 20 and 25 feet in the seam instead of along the bottom as desired. Figure 7 is a map of the affected coal region consistent with thermocouple data and material balance calculations. The map is drawn with the assumption that an average thickness of 7.5 feet of coal was affected.

Figure 7. Detected reverse combustion paths and affected regions during forward gasification on Hanna IV-B.

III. HOE CREEK III

A. Hoe Creek III Thermal Data Analysis

(P. J. Hommert, 4737)

Hoe Creek III, shown in Figure 8, was ignited on day 227 (August 15, 1979). After a brief period of reverse combustion down the drilled borehole connecting the process well, forward gasification was initiated. Gasification was conducted with air for seven days (229-236), then with oxygen/steam injection through the end of the test. The test continued until day 283 (October 10, 1979), with injection rates at approximately 1000 scfm O_2 and 1000 scfm H_2O .

During forward gasification, Well I-2 located 15 meters downstream of the primary injection well and five meters off the line connecting the process wells was intercepted by the gasification process. This well contained the inverted thermocouple string terminated in a transmitter below the coal seam. The arrival of the gasification process was detected first by the thermocouple nearest the coal overburden interface. Shortly after this time, the LLL thermocouple string terminating at the surface failed. Subsequent to this the only source of temperature information below the burn in the Felix 2 seam was the inverted thermocouple system. These data are summarized in Figures 9 and 10. Figure 9 shows time histories for the top five thermocouples. The figure indicates the progressive movement of the gasification process down into the seam.

Figure 8. Hoe Creek III Well Pattern

Figure 9. Temperature histories, inverted thermocouple string. Height above Felix 2 seam floor indicated on graph.

Figure 10. Temperature profiles, inverted thermocouple string. Julian Date indicated on graph.

Once having reached approximately 1200°C, the top three thermocouples track one another indicating that these three have in all likelihood failed. The slower heating rate seen by the 5.05 m thermocouple and its failure to reach gasification temperatures indicate that gasification was no longer active near I-2 during the later stages of the test. Thus gasification was not active over the full surface area at this time. This indicates that there are limitations as to how far the process will progress down from an upper gasification zone.

Figure 10 shows temperature versus depth profiles in I-2 for five days through the test. It is seen that at this location approximately the top two meters of the seam are affected by the process. It is interesting to note that there is no significant heating at the level of the drilled link (3 m) even after 50 days of gasification.

The Hoe Creek III experiment provided an opportunity to apply the burn zone mapping procedure developed for analyzing thermal data from Hanna. This procedure combines material balance and time of arrival information from thermal wells to give a consistent picture of the affected region. Unfortunately, as at Hanna, the usefulness of this technique was significantly compromised because in the majority of wells, first arrival of the gasification front was at the top of the Felix II seam. Since the gasification front is accompanied by conditions sufficient to cause the loss of thermocouple strings, there is very little thermal data from beneath the top of Felix II.

In order to do some mapping, the data from I-2 as to amount of gasification beneath the top of Felix II was assumed to be typical for the wells away from the drilled hole DD-1. Using the thermal data and material balance calculations provided by LLL, an estimate of the affected region was made for them. The result is shown in Figure 11 which shows an estimate of the affected region as of day 275. The figure assumes that within the boundary shown on the plot all of the overlying Felix I seam has been consumed and the top 1.5 meters of the Felix II. There is, of course, no unique boundary that can be drawn from the information available at this time, but that in Figure 11 is at least consistent with the material balance and thermal data.

The inverted thermocouple continued to operate through the end of the test. It will be checked periodically throughout the winter to monitor battery pack lifetime.

Figure 11. Estimate of the Affected Coal Region on Day 275.

B. Surface Electrical Resistivity Network (L. C. Bartel, 4737)

The electrical remote monitoring techniques implemented on a variety of UCG and oil shale experiments are the modified Schlumberger (MS) technique and the direct excitation electrical potential (DEEP) technique. The current electrodes for the MS method are located on either side of the experiment area and separated by approximately five times the depth of the coal seam. The applied current lines for the MS technique are distorted by regions of hot, conductive coal or oil shale leading to a distortion of the electrical potentials at the surface. One current electrode for the DEEP method is a process well and the other current electrode is an outlying well. In the DEEP configuration, the hot, conductive coal (or oil shale) in contact with the process well (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. Both the MS and DEEP techniques use the same surface electrical potential electrode array, share a common current electrode, and use the same measuring hardware.

A comparison* of the reaction zone boundary for the Hanna IV-A test as determined from thermal and DEEP data showed good agreement. The data reduction algorithm used to analyze the data requires the use of a large memory, fast computer because of the integral equation model function. If an algorithm is to be installed on field mini-computers, a model function is needed which requires less storage and computation time than the integral equation solution. Such a model function is the subject of this section.

The alpha center model** is an analytic representation of a three-dimensional conductivity distribution. The model differs from conventional models in that the boundaries between media of differing conductivity are not sharply defined. Instead, the conductivity varies continuously from point-to-point, which is often a better approximation of the gasification (or retorting) reaction zone.

The current density is given by

$$\vec{J} = -\sigma \vec{\nabla} \phi, \quad (1)$$

where J is the current density, σ is the conductivity, and ϕ is the scalar potential. Define two new quantities α and ψ as

$$\alpha = \sqrt{\sigma} \quad (2)$$

and

$$\phi = \psi / \alpha \quad (3)$$

Then the continuity equation ($\vec{\nabla} \cdot \vec{J} = 0$) for J yields

$$\frac{\nabla^2 \alpha}{\alpha} = \frac{\nabla^2 \psi}{\psi} = f \quad (4)$$

where f is the separation constant. For the separation constant equal to zero, both α and ψ satisfy Laplace's equation

$$\nabla^2 \alpha = 0 \quad (5)$$

$$\nabla^2 \psi = 0 \quad (6)$$

*Fourteenth and Fifteenth Quarterly Reports, March through August 1978, Sandia Laboratories Report, SAND78-2311, December 1978.

**R. N. Edwards, H. Lee, and M. N. Nabighian, "On the Theory of Magnetometric Resistivity (MMR) Methods," *Geophysics* 43, 1176-1203 (1978).

Solutions to equations (5) and (6) for a single α -center (conductivity anomaly) are of the form

$$\alpha = C/R + B \quad (7)$$

and

$$\psi = \psi_0 + D/R, \quad (8)$$

where R is the distance between the field point and the α -center, C is the strength of the α -center (represents the conductivity anomaly), B is related to the background conductivity, ψ_0 is related to the zeroth order potential produced by the current sources, and D for this simple case is given by

$$D = C/(Bd), \quad (9)$$

where d is the distance from the current source to the α -center. Equation (9) results from the stipulation that the α -center is neither a current source n or a current sink.

The simple theory outlined above can be expanded to include n α -centers and to include the effects of the earth's surface. The resulting equations for α and ψ are given by

$$\alpha(\vec{x}) = \sum_{i=1}^n C_i g(\vec{x}, \vec{x}_i) + B, \quad (10)$$

$$\psi(\vec{x}) = \psi_0(\vec{x}) + \sum_{i=1}^n D_i g(\vec{x}, \vec{x}_i), \quad (11)$$

where

$$g(\vec{x}, \vec{x}_i) = [(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2]^{-1/2} + [(x - x_i)^2 + (y - y_i)^2 + (z + z_i)^2]^{-1/2}. \quad (12)$$

For the plus current point electrode located at x_+ and the negative current point electrode located at x_- ,

$$\psi_0(\vec{x}) = (I/4\pi) \{g(\vec{x}, \vec{x}_+)/\alpha_+ - g(\vec{x}, \vec{x}_-)/\alpha_-\}, \quad (13)$$

where $\alpha_{\pm}$ means $\alpha(x)$ is evaluated at x_{+} and x_{-} , respectively.

The requirements that the α -centers are neither current sources or sinks leads to a system of linear algebraic equations for the D's

$$\left[\begin{array}{c} n \\ \sum_{k=1}^n c_k g_{1k} + B \end{array} \right] D_1 - c_1 \sum_{k=1}^n g_{1k} D_k = c_1 \psi_{01}, \quad (14)$$

where $g_{1k} = g(\vec{x}_1, \vec{x}_k)$ and $\psi_{01} = \psi_0(\vec{x}_1)$.

To fit the conductivity distribution, the adjustable model parameters are the $C_1, C_2, \dots, C_n, B$, and the positions $x_1, x_2, \dots, x_n$ of the α -centers. The D's are determined using Equation (14).

The computer storage and computational time requirements for the α -center model function allows the implementation of a data reduction algorithm on a field mini-computer. Using the α -center model function discussed above, along with the ridge regression technique discussed in the 14th-15th Quarterly Report, a data reduction algorithm to reduce MS data was implemented on the field mini-computer at the Hoe Creek III site. Because of apparent hardware problems and since the model function for the DEEP data requires a few more variables, a decision was made to implement the algorithm to reduce only the MS data. The model function for the DEEP data is under development and will be used to reduce the DEEP data following the test.

Unfortunately, the MS data over the course of the Hoe Creek III experiment showed little change. This lack of a change is most likely due to the rather highly conducting overburden at the site; this conducting overburden apparently shields the affects of a changing, conducting reaction zone. Since changes in the surface electrical potentials for the MS technique were minimal, the MS data did not lend itself to analysis for mapping the progression of the reaction zone. It is noteworthy that a minimum in the residual for Hoe Creek MS data is obtained for the α -centers to be at the surface of the earth for a two-center model function.

For the DEEP technique, the current is injected along a well casing and directly into the conducting reaction zone. For this reason the DEEP data, as for the Hanna IV-A test, may be able to be analyzed using the model function under development.

The α -center model function will be used to analyze other electrical potential data such as borehole resistivity data from Hanna IV-B and Rock Springs Site 12 and surface potential data from Hanna IV-A and Hanna IV-B and Rock Springs Site 12.

The appeal of the α -center model function is in its simplicity and that only a small computer is necessary to implement a data reduction algorithm. The α -center model function has some shortcomings. This model function is probably not as accurate as the integral equation model function. In addition, there appears to be a non-uniqueness of solutions; i.e., depending on the starting parameters, the final values of parameters may be different, yet there may be only a small difference in the residual. It is not clear at this time if this non-uniqueness is a property of the ridge regression technique. It may be that the ridge regression approach zeros in on local minima and cannot locate the true minimum in the residual.

IV. PUBLICATIONS, PRESENTATIONS AND OTHER COMMUNICATIONS

Publications

1. R. E. Glass (Editor), "Instrumentation and Process Control Development for In Situ Coal Gasification: Seventeenth, Eighteenth, and Nineteenth Quarterly Reports, December 1978 through August 1979, Sandia Laboratories Report, SAND79-2386.

Other Communications

1. B. E. Bader, L. C. Bartel, G. S. Davidson, P. J. Hommert, and R. P. Reed met with the delegation from the Peoples Republic of China in Laramie, WY, on October 22 and 23, 1979. Bartel, Davidson, Hommert, and Reed gave briefings on various Sandia UCG activities. On October 23, 1979, Bader, Bartel, Davidson, and Hommert met with LETC personnel to discuss program plans.
2. B. E. Bader and P. J. Hommert attended the UCG management meeting in Washington, DC, October 30 - November 1, 1979.

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