DESCRIPTIONS OF REVERSE COMBUSTION LINKAGE AND FORWARD GASIFICATION DURING UNDERGROUND COAL GASIFICATION

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INTRODUCTION

From March to July 1976 the Laramie Energy Research Center (LERC) conducted Phases 2 and 3 of the Hanna II Underground Coal Gasification (UCG) Experiment in a 30-ft subbituminous coal seam located at a depth of 270 feet near Hanna, Wyoming (1). The test was extensively instrumented by Sandia Laboratories with the objectives of both measuring the in situ process directly and developing remote measurement techniques that would be appropriate for monitoring future large scale gasification projects. Primary among the remote techniques were passive acoustic, induced seismic and electrical (2). While the data in these areas are still undergoing analysis, the techniques appear promising in their ability to detect regions of affected coal and thereby provide real-time measurement of the process movement. In addition to these remote techniques, extensive thermal data were obtained during the test by thermocouples located within the coal seam. This paper presents information about this gasification test obtained from an analysis of a portion of these thermal data.

DESCRIPTION OF EXPERIMENT

The test utilized the linked vertical well concept for thick seam gasification. As applied at Hanna this involves essentially a two-step process. First, a high permeability link between the process wells is established by means of reverse combustion. This involves injection of high pressure air at one well and ignition at the other. A combustion front is then drawn from the ignition source against the air flow towards the injection well. Once the link is complete, air flow into the seam at lower pressures increases substantially, the direction of front movement reverses, and forward gasification proceeds from the injection well toward the production well.

Figure 1 indicates the process and instrumentation well pattern for the Hanna II experiment. The letter-designated Sandia instrumentation wells contained, along with other measurement devices, typically eight Chromel/Alumel thermocouples at different locations within the coal seam. Additional thermocouples were located in the overburden.

The experiment was conducted in two parts.* Phase 2 involved linkage and gasification between process Wells 5 and 6. Phase 3 was initially an attempt to drive the 5-6 burn as a line toward the 7-8 well line; however, this proved unsuccessful and the bulk of Phase 3 consisted of two-well gasification similar to the 5-6 burn. Most of the interpretations presented herein deal with the more heavily instrumented Phase 2 part of the experiment.

*Phases 2 and 3 were conducted between Days 96 and 152, and Days 152 and 213 (1976), respectively.

ANALYSIS

The majority of the thermal data obtained during the test show very rapid temperature rises. This is the result of sudden exposure to high temperature gas flows and/or the direct passage of the combustion front. There are, however, temperature rises seen during certain parts of the test which appear to be the result of conduction from a high temperature region. In particular, these responses were observed during reverse combustion linkage and the later stages of forward gasification. Such data can be analyzed by conduction models to provide information about the high temperature regions. The analysis constitutes the solution of an inverse problem; i.e., the source will be characterized by observations of its output.

The approach taken for solving the inverse problem in this paper is that of minimizing a least squares comparison of measured data and model calculations. This determines a solution range for the conduction model parameters. Both random search and simplex techniques are used to perform the optimization.

Linkage Analysis

During reverse combustion linkage, the affected coal is confined to a narrow region due to the low flow rates and the fact that thermal energy is propagated into the virgin coal predominantly by conduction (an inefficient transfer mechanism in coal). Thus, for analysis purposes, the linkage path is modeled as a cylindrical path of radius a and average temperature, T_H. Using this model, numerical finite difference calculations were made which included the effects of temperature dependent thermal conductivity and water vaporization. Results indicate that for responses below 200°F, the constant property analytical expression (3),

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

can fit the numerically generated results within ± 5% by adjusting the thermal diffusivity, α, as an empirical function of T_H. In Equation 1, T_A is the initial ambient temperature, r is the radial distance from the sensor to the center of the path and t is the time since the arrival of the path in the vicinity of the sensor. Equation 1 was used to analyze all the low temperature (< 200°F) responses seen during the Phase 2 linkage. During the period from ignition on Day 94 to Day 114, there were thermal responses of at least 5°F at 17 sensor locations with at least one in each of the eight wells nearest the line between process Wells 5 and 6. These data are shown in Figure 2 with the remainder of the responses in these eight wells during Phase 2. The thermocouple locations are expressed in feet from the bottom of the coal seam. For legibility the responses are truncated once a level reaches a temperature sufficient for gasification (taken here as 1500°F) or at an indication of thermocouple failure.

The optimization routines return values for a, T_H, and the position coordinates necessary to specify r. Least squares comparisons were made in four regions: near Wells D and O, between Wells F and G and between Wells A and C. The responses in Wells E and B indicate that the linkage path passed directly by these wells. Also, the speed with which it passed between them and the fact that the E-B line coincides with a major fracture direction makes it plausible that the path proceeded along a fissure near these two wells. Therefore, the data from these wells could not be appropriately analyzed with a conduction model.

The early responses shown in Figure 2 along the Well A-C-F-G line indicate the presence of two separate linkage paths. The leveling off seen in the 5-ft response in Well C indicates that the path near this well probably did not fully develop. The temperature responses seen in the two levels in Well C and one level in Well A are consistent with a linkage path of equal size and temperature to that passing between Wells F and G but one that begins to cool rapidly after about Day 106. At approximately the same time, the F-G linkage path proceeded rapidly from Well E to B which would make this path the preferred flow direction.

Figures 3 and 4 summarize the results of the analysis of linkage data using Equation 1 where for the A-C path an additional term is added to account for cooling after Day 106. Figure 3 compares typical calculated and measured responses for a number of different sensor locations. Figure 4 shows the relative position and size of the linkage paths with respect to the instrumentation wells.

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

1. Typically, the initial temperature increase shown by the measured data is greater than that predicted. This is consistent with the idea that the initial pulse comes from the most active combustion zone whereas the long term response is indicative of the average temperatures in the path behind the combustion front. These temperatures are, of course, lower than the peak combustion temperatures.

2. The low thermal conductivity of coal results in large temperature gradients so that small changes in distance result in large temperature changes. Thus, the most accurate interpretations that can be made from the analyses are those relating to position.

3. Results consistently indicate effective diameters for the linkage path in the range 2.5 to 3.5 ft.

4. The analysis cannot determine accurately the temperature of the path, because temperature has a weak effect on response, and it is also sensitive to fluctuations in flowrate. Therefore, the responses result from heat sources whose strengths may vary widely over the measurement time. The analysis does indicate path temperatures of 900 to 1300°F.

5. The analysis places the center of the primary linkage path 5 ft from Well D, 3.5 ft from Well O, and 4 ft from Well G. Similarly, the other path is 4 ft from Well D and 4.5 ft from Well C.

6. In all the linkage data there is no evidence of thermal override in the coal seam. The Well A-C path remains about 6 ft from the bottom of the coal seam and the Well F-G path about 5.5 ft from the bottom.

7. None of the low temperature responses are inconsistent with either the analytical model itself or the interpretations resulting from the analysis. However, because of the nature of inverse problems (especially when there are many unknowns), these results do not preclude the possibility of other mechanisms or models accounting for the observed responses.

Gasification Analysis

In addition to the data obtained during linkage, the responses measured later by sensors outside the gasified zone can be analyzed with conduction models to determine the boundary of the affected coal zone in the vicinity of the sensor.

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

The model chosen to analyze these responses is that of a fixed wall which experiences a step jump in temperature to some typical gasified zone value at the initial time. In order to account for boundary movement a dummy initial time increment is used. This time increment allows for the establishment of a preheat zone which models the thermal profile preceding a slowly moving boundary. Two-dimensional calculations show that, due to the insulating properties of the coal, a one-dimensional expression can be used to determine the normal distance from the sensor to the boundary even if the boundary is vertically nonuniform.

For the one-dimensional case the appropriate analytical expression (3) is

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

The variables here have the same meaning as in Equation 1 except that x is the distance from the sensor to the nearest point on the boundary. As was the case for the linkage analysis, for low temperature responses the analytical expression in Equation 2 provides good agreement with numerical calculations that include property variations and vaporization when α is an empirically determined function of T_H.

The data analyzed using this model were the responses seen late in Phase 2 in Wells H, I, and J. Plots of these data are presented in Figure 5. The agreement between the measured data and model calculations is quite good and better, in fact, than was seen in the linkage data analysis.

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

1. The final boundary at the end of Phase 2 (Day 152) for the 10-ft to 20-ft levels was approximately 4-5 ft from Well J and 3-4 ft from Wells H and I.

2. The vertical structure of the final boundary was such that it extended about 1 ft further out from the reaction zone center at the 10-ft level than at the 20-ft level.

3. The predominant reason for the time lag between the responses at the lower and higher levels is not the difference in final extent but rather the upper levels just reach the final position later in time. This conclusion implies that the combustion front, at least in the directions perpendicular to the process wells, at later times is not moving uniformly across the seam, but rather it is pivoting about the points of furthest extent near the bottom of the seam. This pivoting movement is illustrated more clearly in Figure 6 which shows a

schematic diagram of the gasified zone boundary movement during the later stages of Phase 2 in the vicinity of Well I. The lines drawn are approximations to the finite thickness boundary (~ 2 ft) containing pyrolysis and gasification regions. They are based on the information obtained from thermal data as to the final position, time of arrival at that position and minimum horizontal velocity just prior to reaching that position. Also, the boundary line on Day 135 is consistent with the contours drawn in Figure 7. The actual data used are for levels in the 10-ft to 20-ft region. The 30-ft and 0-ft responses are distorted by conduction in the over and underburden, respectively. None of the responses outside the 10 to 20 ft range are inconsistent with the extrapolated boundaries indicated by dashed lines in the figure.

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

Data Interpretation

Having completed an analysis of the predominant conduction responses seen during Phase 2, it is of interest to correlate these analyses with the rest of the thermal data in an attempt to picture the structure of the gasified zone as a function of time. Figure 7 represents such an attempt. Figure 7a shows the gasified zone on Day 135 divided into two sections. The dashed line is an average extent for the 0-ft to 10-ft level within the coal seam. The solid line represents an average extent for the 10-ft to 30-ft levels. The reason for such a division is obvious from the considerable difference in areal extent between the two zones indicated in the figure. The primary inputs for constructing these contours are the responses at the lower levels in Wells A and D and the lack of such in the upper levels, extrapolation of the boundaries and arrival times indicated by analysis of the Well H, I, and J data, and the 20-ft responses in Wells F, G and O. The contours were also constrained to agree with LERC's material balance calculations as to the amount of coal gasified. Figure 7b shows the extent of the same two zones at the completion of Phase 2. These contours are more difficult to draw since the only hard data is the boundary near the H-I-J line and, of course, the need to agree with material balance calculations Therefore, it was necessary to extrapolate from the upper level responses in Wells A, D and G to draw the contours on Day 152. The effect of the assymetry in the primary linkage path is evident in the shape of the gasified region.

While continuous boundaries of a gasified zone can be drawn, it is important to recognize that the gasification mechanism probably varies along the boundary. For example, the rapid responses in the low levels of Wells A and C would seem to be characteristic of the advance of a combustion front and it's associated steep temperature gradients. In contrast, the more gradual rises seen in Well D are probably the result of expansion about the linkage path due to a high temperature oxygen depleted gas stream and reduction reactions.

Taken together, Figures 7a and 7b provide a picture of how the UCG process proceeded in the Hanna seam during forward gasification. There is an initial period of rapid horizontal growth at about the level of the linkage path perhaps due to higher in situ permeability in the horizontal direction. During this period the vertical growth is slower and is confined to the region near the injection well and adjacent to the linkage path. Then at some point the rate of horizontal extension low in the seam slows, and during the later stages of gasification the boundary "pivots" about the points of furthest extent and moves towards the roof of the coal seam aided by subsidence.

Three additional observations support this description of the process. First, if the gasified zone expands very rapidly in the lower third of the seam, then one might expect to see some combined convection-conduction heating to upper level thermocouples from below prior to their experiencing high gasification temperatures. Examination of the 15 and 20-ft responses in nearly all the wells shows just that trend. Almost without exception, the upturns at these levels are slower than those seen at the 0, 5, and 10-ft levels. Many of the responses are not unlike what would be calculated by conduction from a high temperature boundary 2 to 3 ft away. Second, induced seismic data (4) on Day 132 indicate a region of affected coal 4 to 6 ft beyond Well A at about the 5-ft level. This again indicates much more rapid expansion at the lower levels since it is clear from material balance considerations alone that at the upper levels the gasified zone can have nowhere near this extent. Finally, passive acoustic source locations in the overburden, which are indications of the zone extending to the roof of the coal seam, are predominantly located to the injection well side of the Well A-C-F-G line. This is consistent with the contours which show greater vertical extent in this region.

CONCLUSIONS

The thermal data analysis indicates the reverse combustion linkage path in the Hanna seam was approximately 3 ft in diameter. The position of the path with respect to the instrumentation wells was mapped and no evidence of vertical override was detected. The analysis of boundary thermocouple data combined with thermal responses from within the gasified zone indicate that the initial stages of forward gasification showed rapid horizontal expansion at about the level of the linkage path, whereas, at later stages vertical movement becomes more rapid and leads to final boundaries that are nearly vertical.

ACKNOWLEDGMENTS

The cooperation of L. A. Schrider, Dr. C. F. Brandenburg, and the many other members of the Laramie Energy Research Center staff in the Hanna experiment is greatly appreciated.

The contributions of R. P. Reed, who designed the thermal instrumentation system and with whom data interpretation was discussed many times are gratefully acknowledged. The Sandia personnel who fabricated and fielded the thermal sensors, operated and maintained the recording instruments, and reduced the data contributed significantly to this research.

This work was supported by the Division of Oil, Gas, and Shale Technology, United States Energy Research and Development Administration. Dr. Paul R. Wieber of that organization is manager of the in situ coal gasification program.

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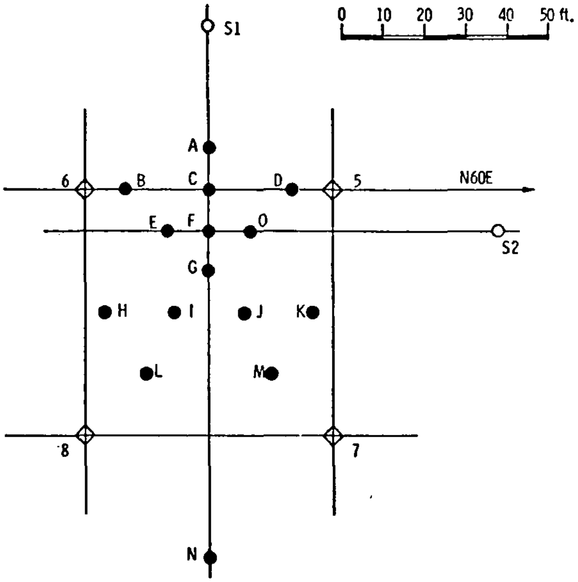


Figure 1. Well Pattern for Phases 2 and 3 of the Hanna II Experiment.

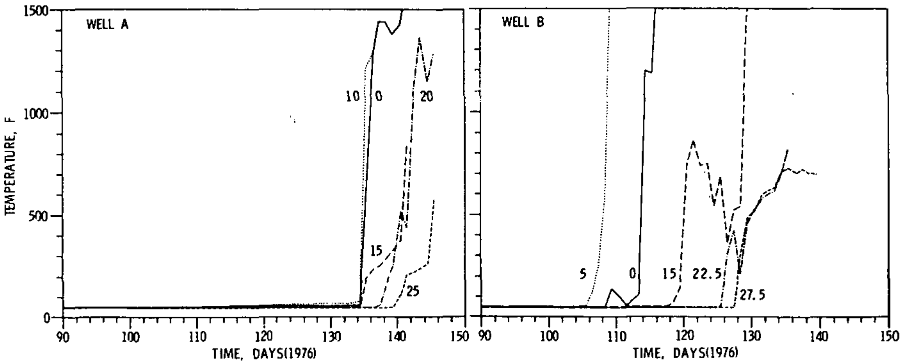


Figure 2a. Temperature-Time Profiles During Phase 2 in Wells A and B. (Thermocouple Locations (feet) Referenced to Bottom of 30-foot Coal Seam.)

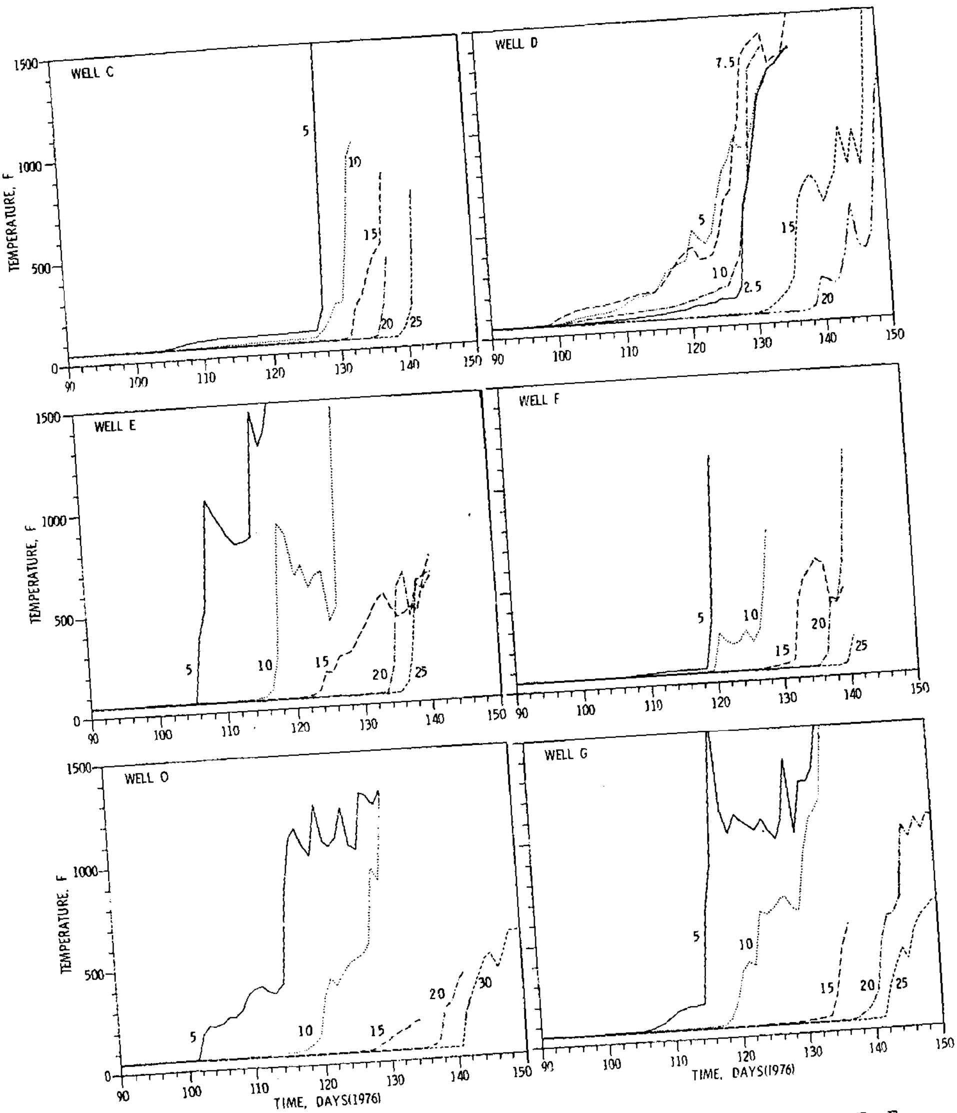
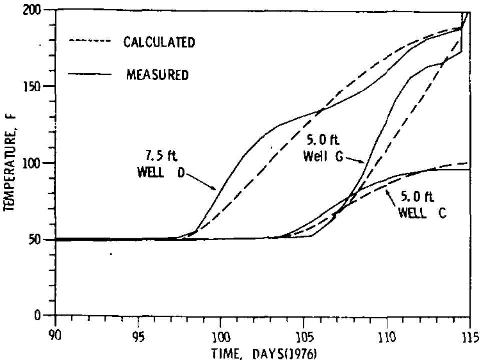


Figure 2b. Temperature-Time Profiles During Phase 2 in Wells C, D, E, F, O, and G. (Thermocouple Locations (feet) Referenced to Bottom of 30-foot Coal Seam.)



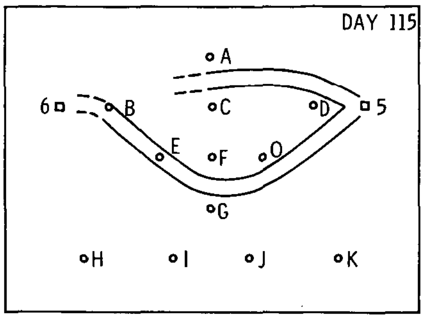
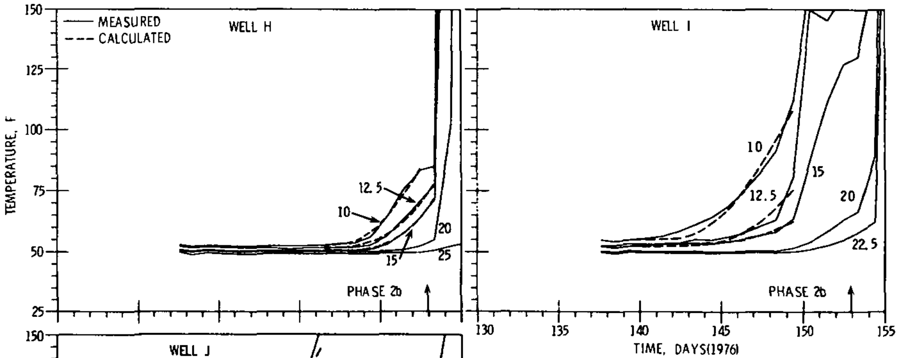


Figure 3.

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

Figure 4.

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.



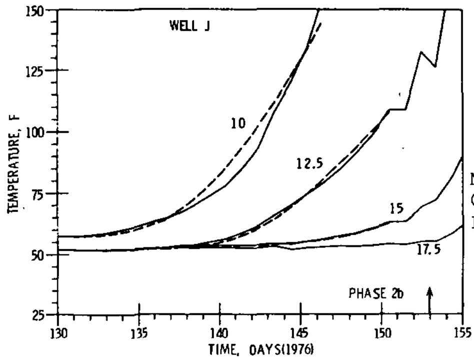


Figure 5

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

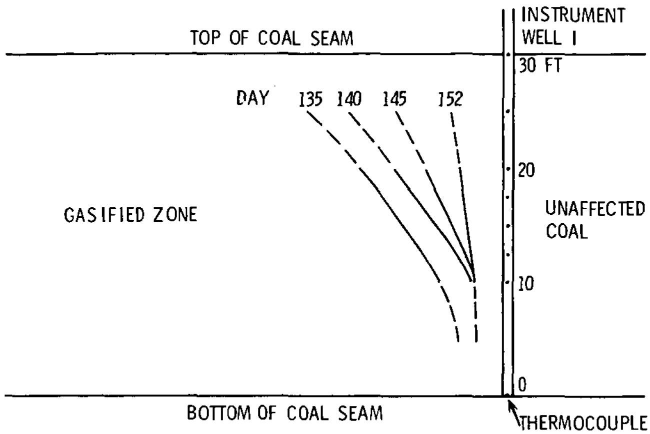


Figure 6. Schematic Diagram of Reaction Zone Boundary Movement Near Well I During Phase 2.

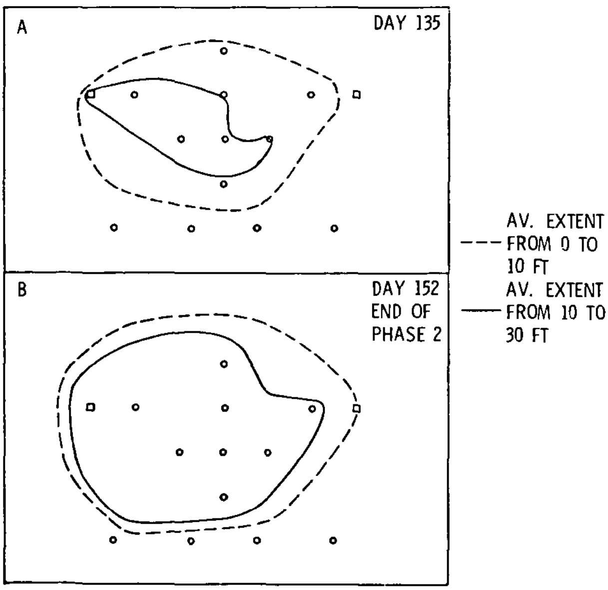


Figure 7. Delineation of Affected Coal Regions at 2 Times During Phase 2. Boundary Locations Based on Thermal Analyses and LERC Material Balance Calculations.