UCRL-50026-79-4

LLL *in situ* Coal Gasification Project Quarterly Progress Report October through December 1979

Scientific Editor: Robert J. Cena
General Editor: Barbara S. Strack

April 23, 1980

Lawrence Livermore Laboratory

CIRCULATION COPY
SUBJECT TO RECALL
IN TWO WEEKS

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

UCRL-50026-79-4
Distribution Category UC-90c

LLL *in situ* Coal Gasification Project Quarterly Progress Report October through December 1979

Scientific Editor: Robert J. Cena
General Editor: Barbara S. Strack

Manuscript date: April 23, 1980

LAWRENCE LIVERMORE LABORATORY
University of California • Livermore, California • 94550

Available from: National Technical Information Service • U.S. Department of Commerce
5285 Port Royal Road • Springfield, VA 22161 • $6.00 per copy • (Microfiche $3.50)

CONTENTS

Summary (R. J. Cena) 1
Introduction (R. J. Cena) 1
Hoe Creek No. 3 2
Summary of Thermal Data in the Vicinity of DD-1 (C. B. Thorsness) 2
Late Burn Boundaries for the Hoe Creek No. 3 Experiment (C. B. Thorsness) 5
Surface Subsidence Associated with the Third UCG Experiment at Hoe Creek (Harold Ganow) 7
Hoe Creek Experiment No. 3—Postburn Evaluation of Process Wells (Don Thompson) 12
Water Quality Measurements at Hoe Creek No. 3 (Francis Wang and Warren Mead) 13
Hydrologic Effects Resulting from Aquifer Interconnection at Hoe Creek No. 2 and No. 3 (Ellen Raber, Randolph Stone, and Francis T. Wang) 15
Deep 1 Experiment 23
Investigation of Potential UCG Sites in Wyoming (Randolph Stone, K. P. Puchlik, J. L. Wagoner, and R. D. McArthur) 23
Preliminary Plan for the Deep 1 Experiment (D. R. Stephens and R. W. Hill) 29
Uniwell Method 33
A New Method for the *In Situ* Gasification of Thick Coal Seams—The Uniwell Method (Richard W. Hill) 33

LLL *in situ* Coal Gasification Project Quarterly Progress Report October through December 1979

SUMMARY

The major effort this quarter has been post-experiment analysis of Hoe Creek No. 3 and planning for future gasification experiments.

Hoe Creek No. 3: Thermal data have been analyzed to determine the performance of the drilled horizontal channel during forward gasification. Thermal and material balance data are combined to determine late-time burn boundaries for the experiment. Surface subsidence after the experiment was completed is described. Process wells were inspected to determine failure characteristics and pinpoint late-time injection location. Ground-water quality before and after Hoe Creek No. 3 and the effects of aquifer interconnection on hydraulic measurements at the Hoe Creek No. 2 and No. 3 sites are discussed.

Future experiments: Potential UCG sites are being characterized for future tests. Two sites in the Powder River Basin near Gillette, Wyoming, are discussed. Preliminary plans for a deep site gasification experiment and a new method for *in situ* gasification of thick seams are presented.

INTRODUCTION

A major objective of the U. S. energy program is to develop environmentally acceptable and economically sound ways to produce energy from the nation's vast supplies of coal.

As a part of the DOE Underground Coal Conversion Program, the basic goal of the LLL project is to develop a process for producing medium heating value gas that can be economically upgraded to pipeline quality gas (SNG) or used as a chemical feedstock. Since gasifying coal with air produces a gas contaminated with nitrogen, thus lowering the heating value, we are concentrating our efforts on gasification using oxygen and steam as the injectant. We gratefully acknowledge the co-sponsorship and co-funding of this project by the Gas Research Institute.

HOE CREEK NO. 3

SUMMARY OF THERMAL DATA IN THE VICINITY OF DD-1

To understand the performance of the Hoe Creek No. 3 experiment, it is important to understand the way in which the originally drilled horizontal hole (DD-1) grew. After cursory examination of the thermal data from wells in the vicinity of DD-1, two views of the location of the product gas flow and evolution of DD-1 seem reasonable. The first possibility is that very early in the experiment, the hot gas stopped flowing down DD-1 and jumped to a new path near the top of the coal seam. This behavior would be very much like the behavior of our Hoe Creek No. 2 experiment. The alternate view is that the flow path of the hot product gas did not jump suddenly to a new path, but instead the initial channel established by DD-1 at 2–3 m from the bottom of the seam grew with time. This growth was primarily upward and, after some time, the main flow of hot product gas moved from injection to production points near the top of the seam.

A detailed examination of the thermal records of the instrument wells near DD-1 (I-3, I-5, W-2a, I-11, I-12, and I-15) seems to support most strongly the latter view of a continuously evolving channel, which grew much more rapidly up, then out.

Three thermal wells (I-5, I-12, and I-15) clearly indicate a continuous growth upward of the original DD-1 channel. Well I-5 (Fig. 1) appears very close to DD-1. An increase in temperature at the 2-m level can be seen as early as day 229.3 (forward gasification began on day 229.5). It is possible that the first part of this response was driven by the close passage (within 0.1 m) of gases associated with the reverse burn, which occurred between days 228.5 and 229.3. The data are not, however, conclusive. Low-temperature responses (temperature less than ~200°C) move progressively up the I-5 well from day 229 to day 237, when a thermal response of the 7-m level is noted. High-temperature responses (temperature greater than ~400°C) are first noted at the 3-m level in I-5 on day 231. No other high-temperature responses occur until days 239–241 when the 5-, 6-, and 7-m levels respond. This behavior of I-5 seems consistent with the theory that DD-1 grew primarily upward and then spread laterally near the top of the coal seam.

Wells I-12 and I-15 both appear to have been somewhat further from DD-1 than I-15, on the order of 0.5–1.0 m. Well I-12 saw low-level conduction responses at the 2-, 3-, and 4-m levels, with the 2-m level response associated with a source about 0.5 m away on day 229.5, and the 3- and 4-m responses associated with sources 0.2 and 0.6 m away, respectively, on day 231.5. Levels 6 and 7 saw a steam source response on days 240 and 242, respectively. Higher level temperature responses were only seen at the 6-m and above locations. The 6-m response came on day 242, while those at 7 and 8.5 m arrived near day 247. The behavior of I-12, again, substantiates the upward growth hypothesis.

Well I-15 (Fig. 2) saw conduction-level responses somewhat later than I-12, indicating it might be a little further away from DD-1 than I-12. Conduction responses were seen at 2 and 3 m, associated with a source 0.4 to 0.6 m away on day 232.6. The 4-, 5-, and 6-m levels saw responses associated with a source 0.4 to 0.8 m away on day 235.5. High-level responses occurred only at 6 m and above. The 6-m response came on day 247 and the 7-m response on day 248. These results seem consistent with the hypothesized upward growth of DD-1.

The data from wells I-3, W-2a, and I-11 do not directly support an upward growth. These wells, for the most part, only saw responses in the upper portion of the seam, thus indicating a source high in the seam. However, the responses were all generally late (days 240–250). It is known that these wells were located 2 m or more from DD-1. Significant thermal responses will not propagate through 2 m of coal in any reasonable amount of time. It would seem then, that these wells could well have missed the early history of DD-1, since they were too far away, and only responded to the later behavior associated with the spread of the channel near the top of the coal.

In summary, we feel that DD-1 did effectively direct the flow down through the coal at the beginning of the experiment. However, the drilled hole grew primarily upward through the first 10–14 days of the burn and allowed the connecting link between injection and production wells at the top of the coal seam by day 242.

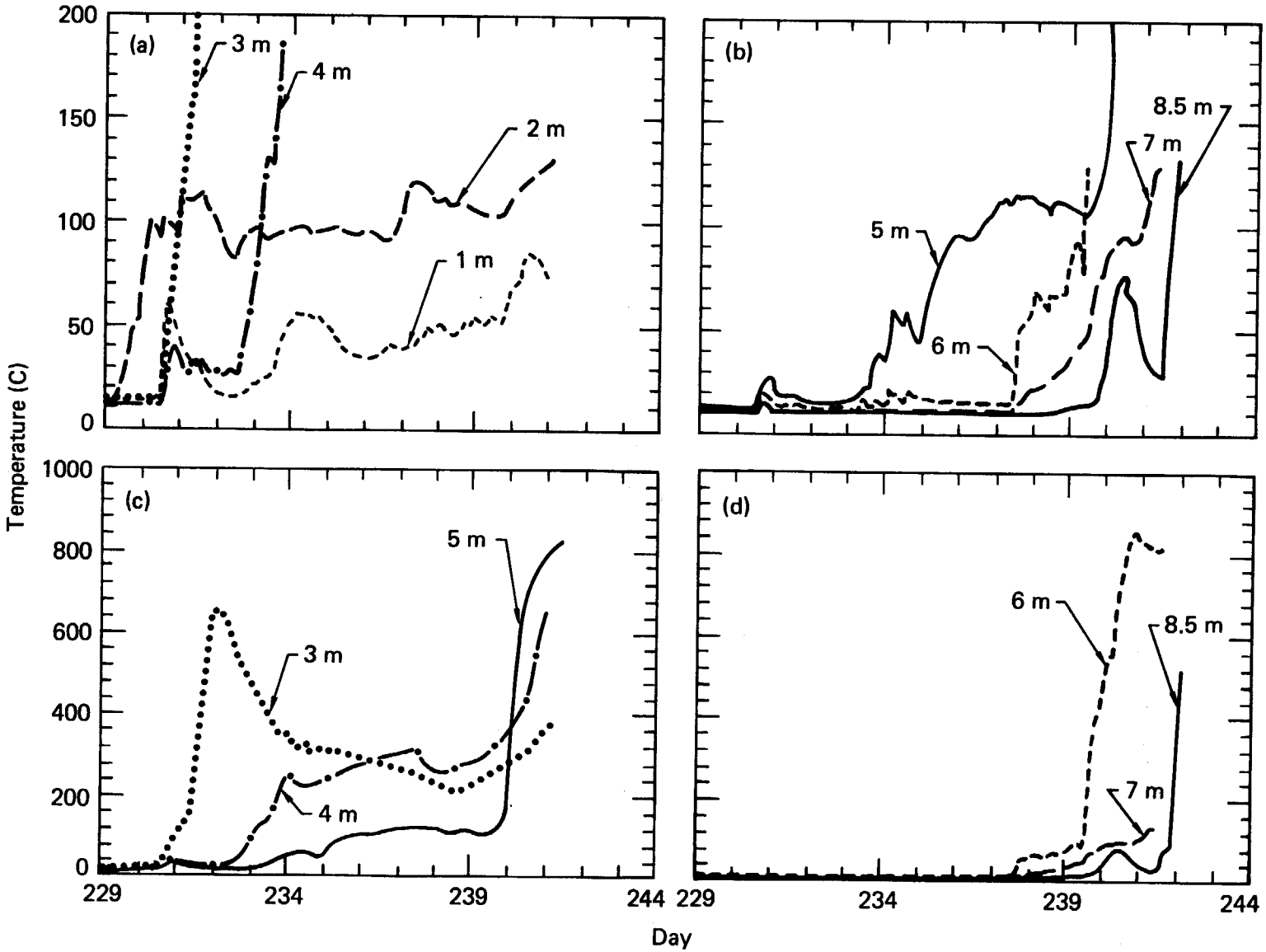

FIG. 1. Thermal responses of well I-5, which was located near DD-1: low temperature responses (1a and 1b), and high temperature responses (1c and 1d). Distances are measured from the bottom of the Felix No. 2 seam.

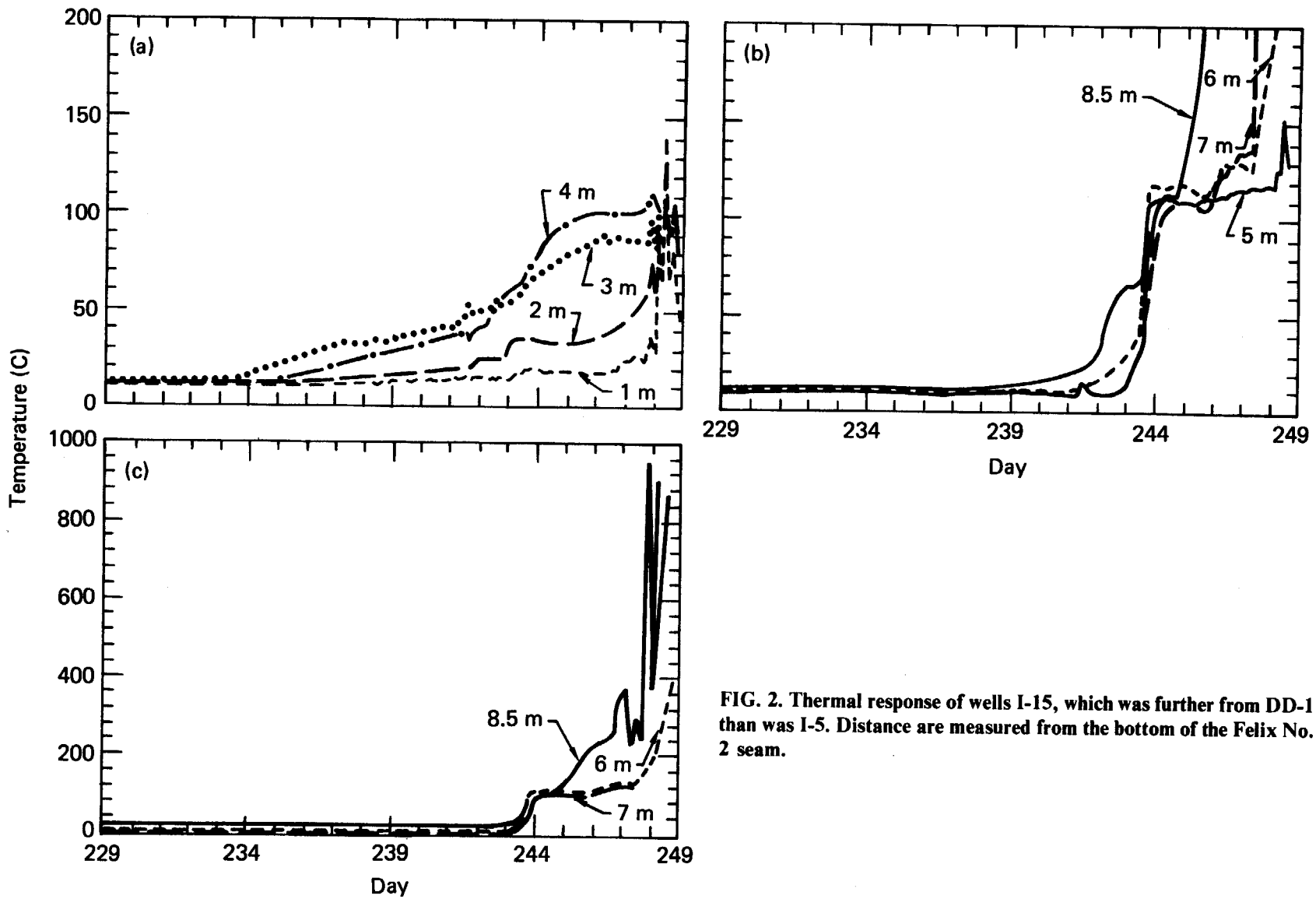

FIG. 2. Thermal response of wells I-15, which was further from DD-1 than was I-5. Distance are measured from the bottom of the Felix No. 2 seam.

LATE BURN BOUNDARIES FOR THE HOE CREEK NO. 3 EXPERIMENT

During a gasification experiment, it is quite important to know where the burn boundaries are. The extent of the consumed coal region is obviously of concern in dealing with process economics and in understanding the gasification process itself. We have made a first attempt to pin down the middle and late burn boundaries. Our estimates are based on thermal data and material balance considerations for the Hoe Creek No. 3 experiment.

A total of 2816 m^3 of coal was consumed during the Hoe Creek No. 3 test. This number includes corrections for the gas lost (estimated to be 17%) during the experiment. We estimated the coal consumed by assuming that the lost gas had the same composition as product gas. With no correction for gas losses, the total coal consumed is 2316 m^3. This latter number would be valid only if all lost gas had the same composition as the injection gas. We consider this unlikely, and will use the gas-loss-corrected number and thermal data to infer the burn boundaries.

The thermal data on burn-boundary location is limited, especially in the Felix No. 2 coal seam and in the vicinity of the main injection well, P-1. As a result, the following description of burn-boundary locations is tentative. Coring is necessary before we can estimate the final burn boundary with reasonable confidence.

Figure 3 shows the proposed burn boundaries at the end of the experiment. The dotted line represents the extent of burning in the 3-m thick Felix No. 1 seam (estimated at 970 m^3) while the solid lines represent the burn boundaries in the 7.7-m-thick Felix No. 2 seam (estimated at 1846 m^3).

We have assumed that, in the Felix No. 2 seam, the unburned boundary can be represented by an outward-sloping volume. Lines representing the 0-, 3-, and 5.7-m burning levels (measured from the top of the seam) are shown. It is assumed that the central region running from P-1 to well B is flat, about 3.5-m wide, and 5.7-m deep in the seam. There is no thermal evidence to justify this assumption. The 5.7-m depth was chosen to coincide with the original location of DD-1; the 3.5-m width was chosen to yield the appropriate coal consumption. The slope was derived solely from the information

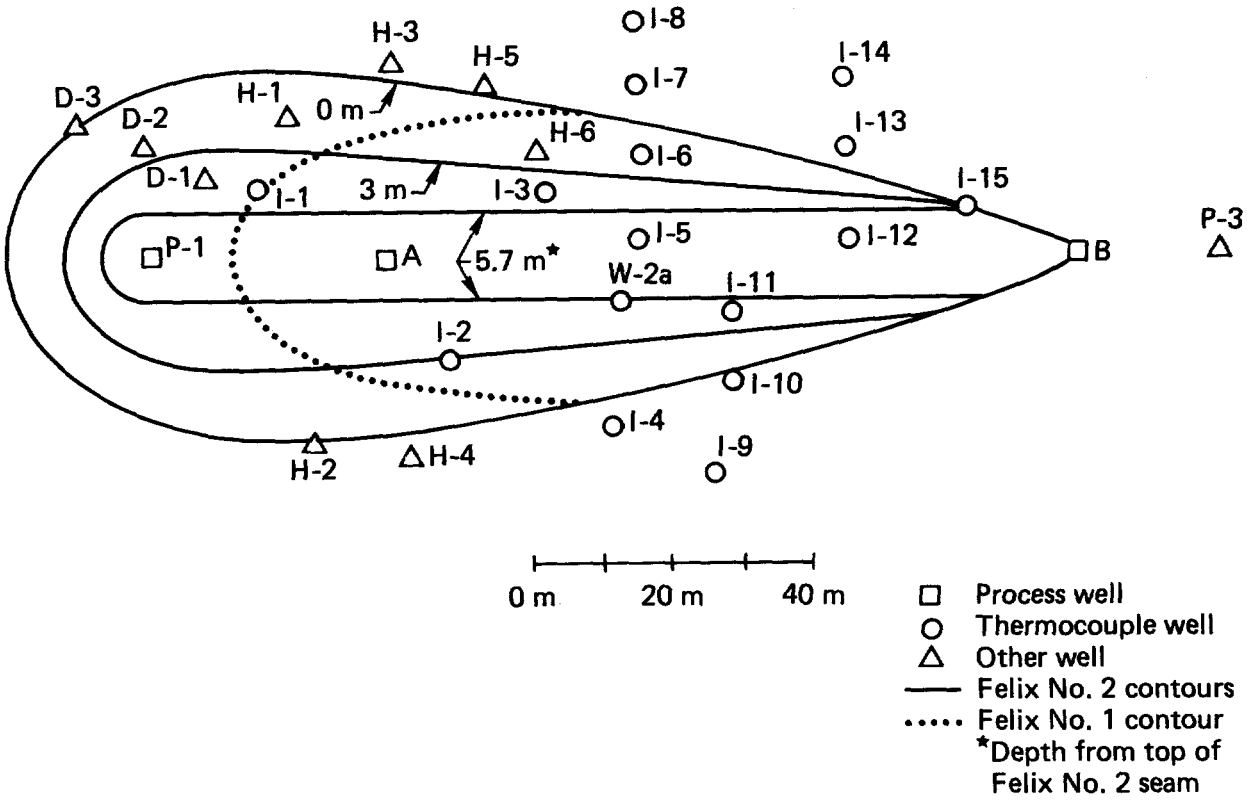

FIG. 3. Final burn boundaries in the Felix No. 1 (dashed lines) and No. 2 (solid lines) coal seams.

provided by the inverted thermocouple in I-2, which indicated a maximum burn depth of 2.5–3 m. The outer boundary was drawn to be consistent with the lack of thermal responses from I-4, I-7, I-10, and I-13 and a total of 1846 m^3 of coal consumed for Felix No. 2.

The dotted line in Fig. 3, representing the extent of burn in Felix No. 1, was drawn to be consistent with thermal data. The line represents the extent of a burn that would have taken 100% of the Felix No. 1 coal if it had vertical sides. If we assume that the sides are sloped, the outer burn boundary could be extended. The only direction for a large extension would be towards P-1, because the boundaries set nearer the production well (B) are drawn to agree with thermal data. The shape of the boundary drawn was strongly influenced by our knowledge of the location of the surface subsidence, which occurred after the end of the experiment. The main subsidence crater is between A and B wells, centered approximately 6–8 m from A well. We could not justify this crater location on the basis of coal consumption from Felix No. 2 alone, and therefore felt compelled to skew the Felix No. 1 burn boundary toward the B well, because the coal removed from this upper seam could have influenced the location of the subsidence more than the coal from the lower Felix No. 2 seam. This skewed burn is also supported to some extent by the strong indications of a burn in Felix No. 1 while oxygen was injected into well A.

Trying to tie down the burn boundary at a time other than the end is not easy. We have, however, attempted to sketch the burn boundary midway through the burn, day 258.5. This boundary is shown in Fig. 4. The total estimated coal consumed at day 258.5 is 1400 m^3 with an estimated 730 m^3 in Felix No. 1 and 670 m^3 in Felix No. 2. The odd shape of the Felix No. 1 burn was drawn to account for material balance considerations and the fact that we had injected considerably more flow in well A by day 258.5 than in well P-1.

The burn boundary for Felix No. 1 in Fig. 4 again reflects the assumed vertical-walled, 100%-consumption boundary. In drawing this boundary we considered the available thermal data and were influenced by our belief that coal was consumed in Felix No. 1 at the highest rate early in the experiment, particularly when oxygen was injected into well A.

The Felix No. 2 burn boundary shown in Fig. 4 reflects the zero-burned boundary at the top of the seam. We assumed that, at this stage, the burned-out region sloped downward from this boundary to the P-1 to B centerline, where the depth was 5.7 m.

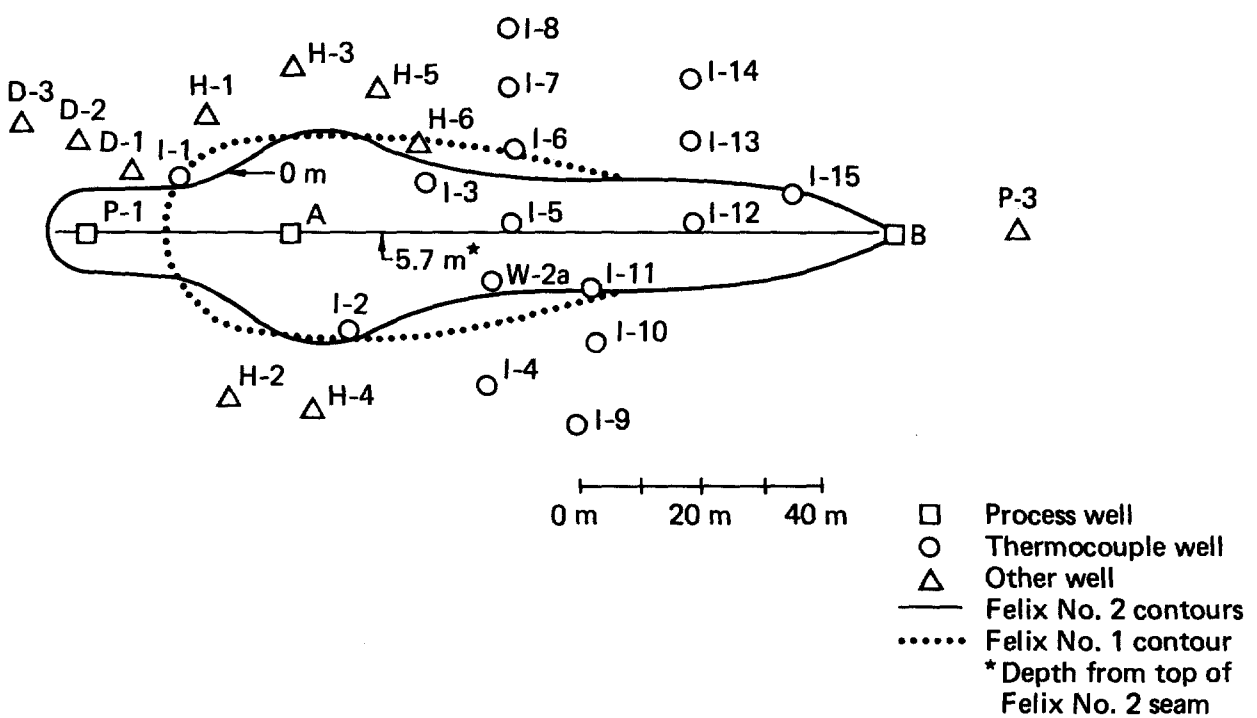

FIG. 4. Burn boundaries in the Felix No. 1 and No. 2 coal seams on day 258.5 (half-way through the burn).

SURFACE SUBSIDENCE ASSOCIATED WITH THE THIRD UCG EXPERIMENT AT HOE CREEK*

We first observed subsidence at the ground surface over the site of the third UCG experiment, Hoe Creek No. 3, on November 2, 1979 (day 306). We saw a small, approximately circular depression or sink measuring about 2 m (6.5 ft) in diameter and about 1 m (3 ft) deep. Sink I, as it was subsequently named, appeared 77 days after forward burn began at Hoe Creek No. 3 and 23 days after the experiment ended. It is located about 4.3 m (14 ft) from A well along the centerline of the experiment, drawn between process wells A and B. The material in the bottom of the sink is quite broken and soft and, at first, relatively large amounts of steam were released from it. A permeable connection to the hotter portions of the gasification cavity is clearly indicated.

The growth and evolution of surface subsidence features were photographed and mapped for five days, beginning on November 3rd (day 307), by the auther, assisted by Patrick Burkland. Fortunately, the weather was clear enough during this time for detailed observations and mapping of ground fractures and repeated surveys of ground motion monuments (placed before the experiment). It must be emphasized that only the initial stage of the overall subsidence has been observed and that it will continue to subside for some time.

Figures 5 through 9 show the ground surface features for days 307 through 311. Figure 5 is a plan view drawing of the ground surface features on day 307. They consist of Sink I, whose origin has already been discussed, and several hair-line fractures located in the same general pad area as the depression. The fractures were marked with a different color spray paint for each of five consecutive days. On day 307, there are two distinct types of

*Support for these investigations is provided by the Division of Environmental Control Technology (DOE/ASEV), the Office of Research and Development (EPA/IERL-CI), and the Division of Fossil Fuel and Extraction (DOE/ASET).

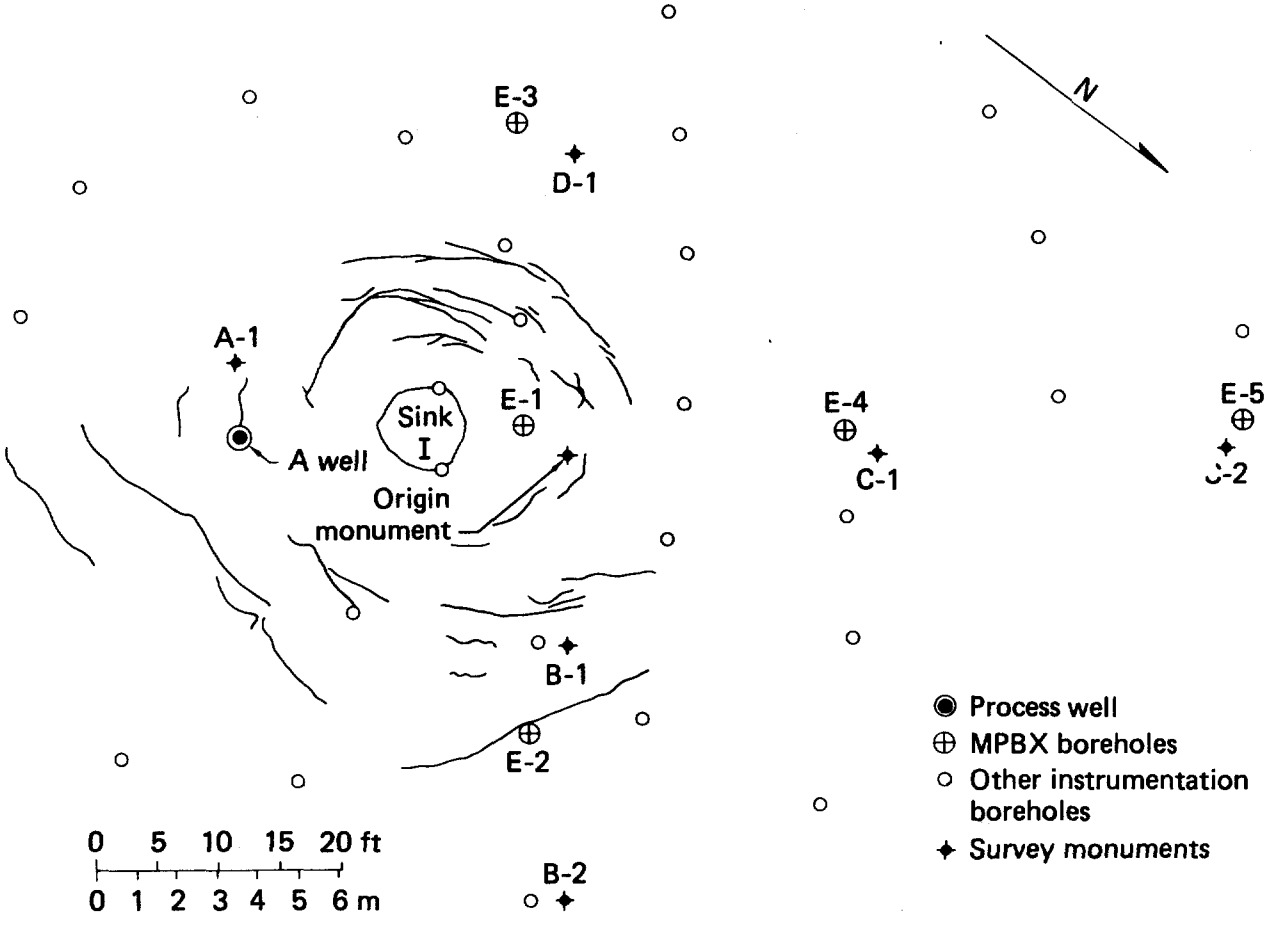

FIG. 5. Ground surface features on November 3, 1979 (day 307).

fractures. The most prominent fractures are mainly concentric to Sink I and are principally located to the "upper right" of this feature. The second fracture set consists of cracks whose orientation and overall character appear to be controlled by some other source, such as the general shape of the main burn cavity located deep underground. These less-prominent fractures are mainly located further from Sink I and, on day 307, are best developed to the "lower" and "lower left" of Sink I. Note that the fracturing has developed a strong asymmetry toward the "lower portion" of the pad area near borehole E-2.

Figure 6 (day 308) shows continued growth of both Sink I and the fractures in the experiment pad surface. Sink I grew mostly as the result of the rim collapse, which was caused by steam-induced softening of the surficial materials. No downward movement of the sink floor could be detected, although the steam flow made careful depth-measurement impossible. Existing fractures extended, new cracks formed between pre-existing cracks or where fractures filled in, and a new group of fractures formed to the "right" and "upper right" of Sink I. Note that the fractures near borehole E-4 are strongly oriented transverse to the experimental axis. Fracture extension and infilling clearly indicate that this portion of the pad surface is still strained by both vertical settlement and block rotation, and that the strain gradient is increasing. The new group of fractures is a strong indication that major rock collapse has recently occurred near the ground surface in this region.

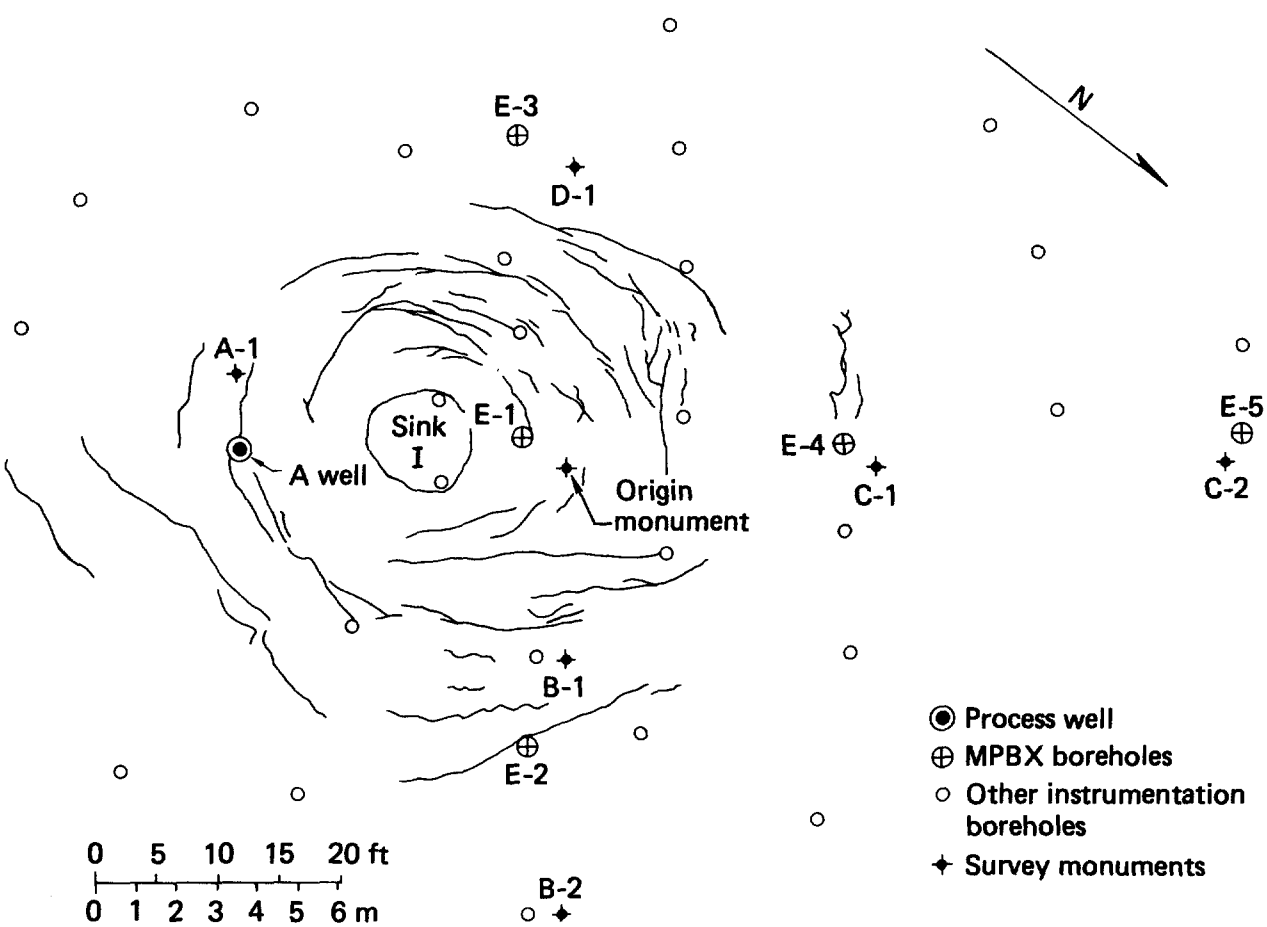

FIG. 6. Ground surface features on November 4, 1979 (day 308).

Figure 7 (day 309) again shows that Sink I and the surface fractures grew in a manner similar to the previous day. Fracture growth, infilling, and neoformation are, for the most part, uniformly distributed about the pad area. The features are an area of miniature thrust faulting (to the "upper left" of Sink I) and thin, delicate surface buckles (to the "right" of Sink I). Also, the ground surface in this latter area is becoming finely fractured and almost granular in appearance, and it indents easily under modest pressure. These features indicate a relatively high horizontal state of stress, probably oriented perpendicular to the experimental axis. This circumferential or "arching" stress is increasing as the cavity roof in the pad area becomes progressively thinner because of subsurface collapse. The weathered and comparatively weak rock and soil at the ground surface are actually failing in compression; the result is loose granular texture.

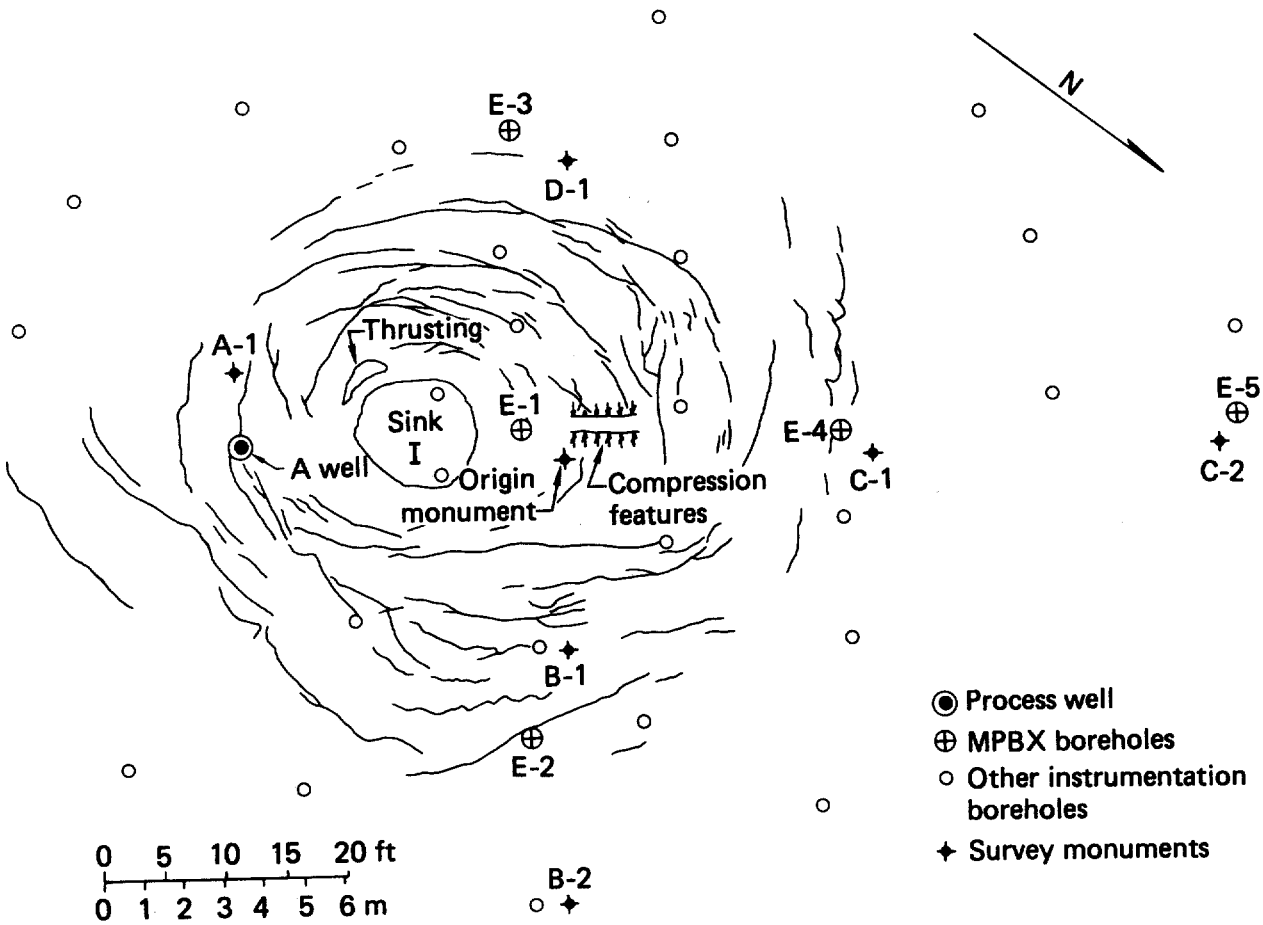

FIG. 7. Ground surface features on November 5, 1979 (day 309).

Sink II appeared catastrophically on day 81 and its location is shown on Fig. 8. It initially measured about 2 m (6.5 ft) in diameter and was about 3 m (10 ft) deep. The sink walls appeared to be nearly vertical, although steam emerging from the sink and surficial materials cantilevered about the opening prevented a clear view. Many new fractures appeared (above, below, and to the right of Sink II) in response to continuing subsurface collapse in this region. Other cracking was observed only about the margin of the previously fractured area and was clearly under the influence of the subsurface burn cavity.

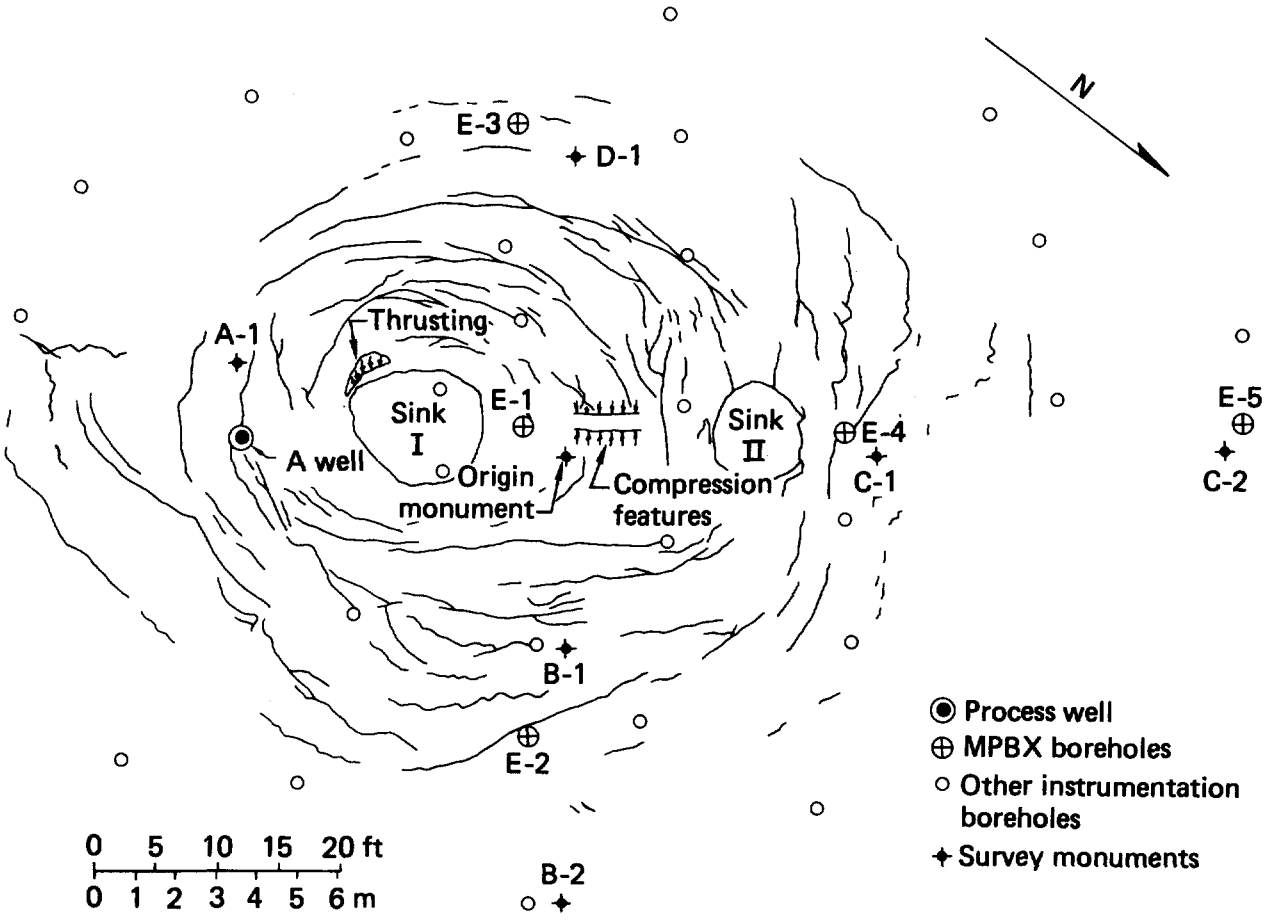

FIG. 8. Ground surface features on November 6, 1979 (day 310).

Figure 9 shows moderate growth of Sinks I and II and the continued formation of new fractures located principally about the margin of the previously fractured area. The pad area between boreholes E-4 and E-5 was carefully examined. Here, several pre-existing arrays of shrinkage cracks seemed to have widened in a manner suggesting strain toward the pad center, but we observed very few well-developed fractures. Several new fractures appeared in the "lower" part of the experiment pad near borehole E-2, again suggesting an asymmetrical burn cavity in the subsurface. Other major fractures were observed "above" Sink II and were undoubtedly associated with its formation. The sinks grew by continued slump-rounding of the edges (Sink I) and by collapse of cantilevered material (Sink II).

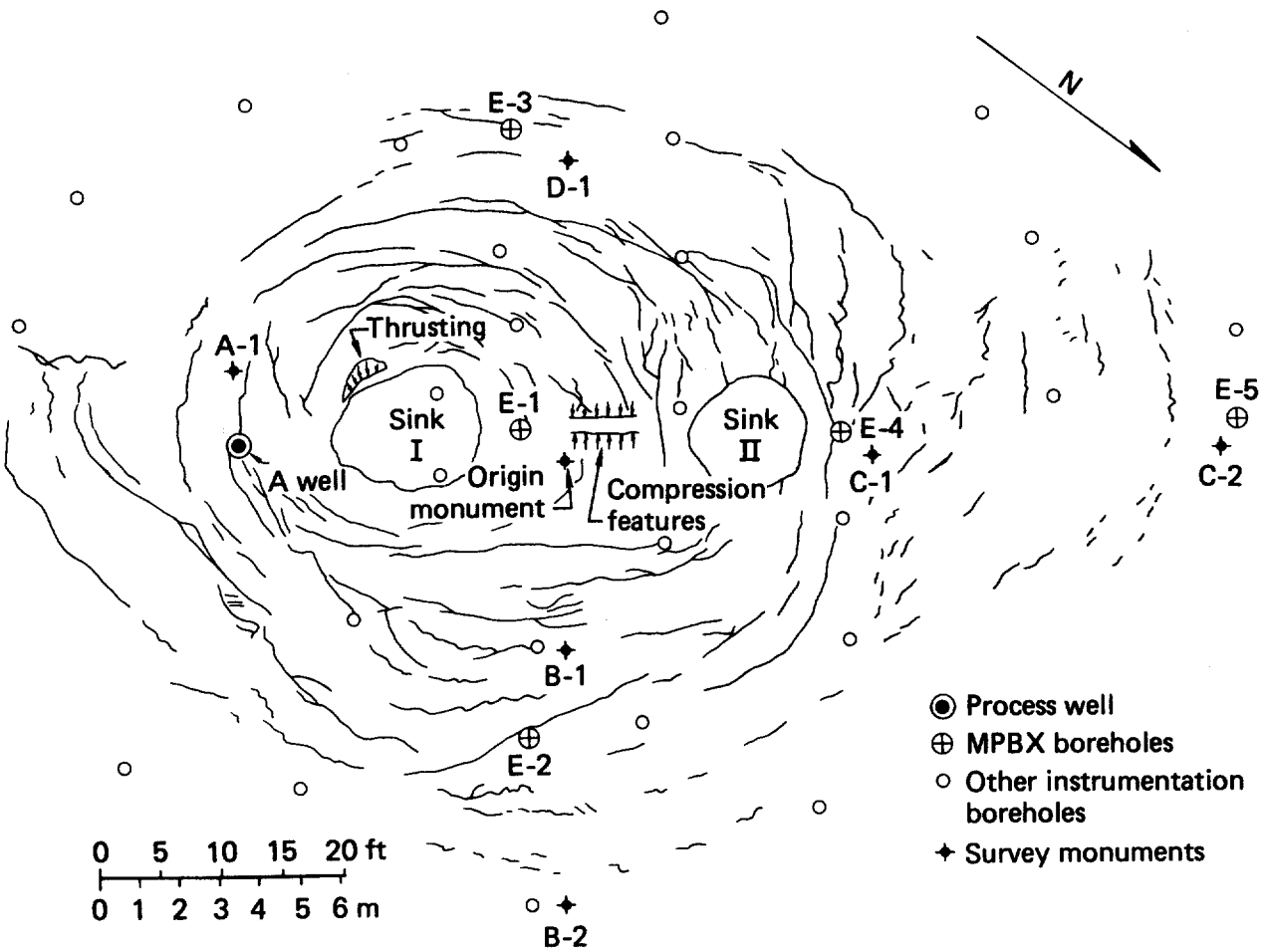

FIG. 9. Ground surface features on November 7, 1079 (day 311).

The following conclusions are tentatively advanced with regard to the initial stages of surface subsidence thus far observed at Hoe Creek No. 3.

1. The physical features and motions observed at the ground surface at Hoe Creek are consistent with a chimney or stope failure. This is a "progressive" failure during which materials suspended in the immediate cavity roof suddenly collapse to the floor and expose new materials, which in turn collapse, and so on. This cycle continues at a varying rate until bulking of the collapsed rock (that is, the collapsed rock occupies a volume greater than its initial volume) fills the void, which is moving up through the overburden, or the cavity intersects the ground surface and results in surface subsidence.

2. Initially, surface fracturing observed at Hoe Creek No. 3 was concentric to, and probably resulted from, subsurface adjustment associated with the appearance of Sink I. In fact, Sink I can be thought of as a "pilot stope" that preceded the main collapse zone to the ground surface. Subsequent fracturing was not concentric with either Sink I or II; we think it represents, in part, the areal disposition of the principal combustion cavity in the Felix coals. Therefore, the lateral asymmetry of fracturing previously described is thought to reflect an asymmetric burn cavity underground. In the vicinity of borehole E-4, surface fractures exhibit a distinctly perpendicular trend to the experimental axis, suggesting an abrupt change in deformation style. It seems likely that the ground surface to the "right" of E-4 will remain essentially stable, while the region to the "left" will undergo large settlements. Sink II probably resulted from a cavity caused by material flowing down the "back side" of the rubble pile into the relatively more confined and stable portion of the cavity located near B well.

3. Both vertical and horizontal motions can be expected indefinitely at Hoe Creek No. 3. This motion will be caused by continued consolidation of the highly porous cavity rubble, influenced by its own weight and adjustments to the highly modified *in situ* state of stress. There is no way to accurately predict the magnitude of these motions or when they will no longer be detectable. However, we expect total vertical motions of 3–5 m and it is likely that continued significant movement will be detectable for at least ten years.

HOE CREEK EXPERIMENT NO. 3—POSTBURN EVALUATION OF PROCESS WELLS

During the shutdown phase of Hoe Creek Experiment No. 3, a limited inspection of most of the process wells was conducted. This was undertaken to determine how well the wells survived the test and to assist in providing some insight into burn cavity geometry. Following is a summary of the results of this investigation.

Well P-1

The P-1 well was originally designed as a dewatering pump well; it also was designed as the alternate injection well and was used as the injection well for most of the oxygen phase of the experiment. The copper (3-inch in diam) lance used for injecting the oxygen to the lower region of Felix No. 2 was removed. This pipe had been melted at an elevation approximately in the middle of the Felix No. 1 coal seam. Approximately 35 ft of the pipe had been consumed. Neither the wall thickness nor the diameter of the pipe had been reduced at the point of failure, indicating the pipe was under very little stress at the time it was undergoing this extensive thermal damage.

The remaining internal piping in the well was all carbon steel and failed from severe oxidation and some tensile loading at an elevation immediately above the Felix No. 1 coal seam. The bottom of the well was tagged at 146 ft below ground level, which is a few feet below the Felix No. 1 coal seam. Indications are that the well had silted because the casing and liner failed at that level.

Well A

The A well designed as the primary injection well was used for the air injection phase and for a short period of the oxygen injection phase of the experiment.

The oxygen lance was removed from this well and found to be ruptured at roughly the elevation of the bottom of Felix No. 1 coal seam. The broken section was a 3-in. schedule-40 pipe made of Monel. The rupture occurred in the threaded area at the point of entry into a mating, threaded coupling. The Monel pipe was also bent through approximately a 10° angle around a point 5 ft from the ruptured end of the pipe. There was no evidence of any damage to the pipe as a result of high temperatures.

The degree of bending this pipe could undergo would have been limited because subsequent displacement would have been constrained by the well casing liner and casing. It can only be assumed that the well casing and casing liner were laterally displaced to the same degree as the oxygen liner.

The A well was tagged and found to have collapsed at a point two feet below the point at which the oxygen liner had ruptured, in Felix No. 1 coal.

Well B

The B well was found to have failed (collapsed) at a point well above (~10 ft) the Felix No. 1 coal seam. The piping removed from this well was found to have been consumed (by corrosion) below a level approximately 100 ft below ground level, which is 30 ft above Felix No. 1 coal. Also, the wellhead was filled with what appears to be mostly slag; flow passage through the well was almost plugged.

Well P-1

The P-1 well, a well 20-ft downstream (on the C-well side of B well) of B well was opened and the pump was removed. All internal parts appeared to have survived the environment. Some evidence of high temperatures (corrosion) at the Felix No. 1 elevation was visible. The well was intact to its original depth below Felix No. 2—it had not collapsed as was the case for the other process wells.

WATER QUALITY MEASUREMENTS AT HOE CREEK NO. 3*

Before the Hoe Creek No. 3 experiment began, we constructed 15 water wells in the Felix No. 2 coal and overlying aquifers for environmental measurements (Fig. 10 and Table 1). Baseline water quality was also measured before gasification.

*Support for these investigations is provided by the Division of Environmental Control Technology (DOE/ASEV), the Office of Research and Development (EPA/IERL-CI), and the Office for the Deputy Assistant Secretary for Oil and Gas Technology (DOE/ASFE).

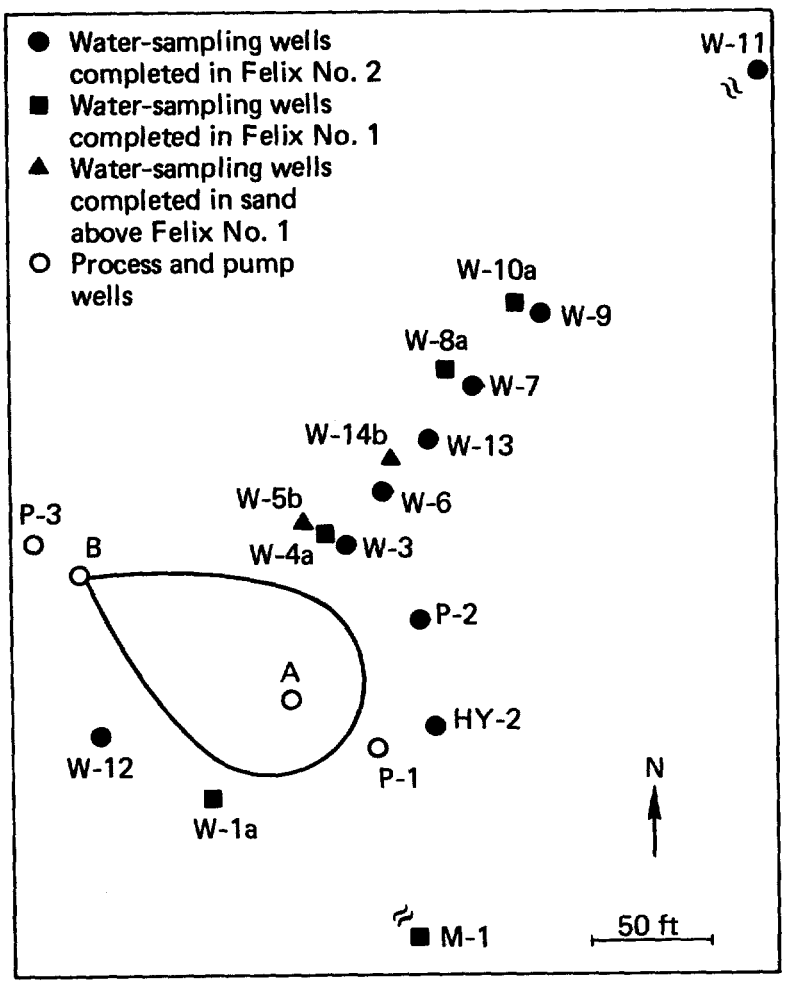

FIG. 10. Location of water sampling wells near the Hoe Creek No. 3 gasification experiment.

TABLE 1. Information on water-sampling wells at Hoe Creek No. 3.

Well	Aquifer	Distance to well A (ft)
W-1a	Felix No. 1	70
W-3	Felix No. 2	93
W-4a	Felix No. 1	94
W-5b	Sand	95
W-6	Felix No. 2	132
W-7	Felix No. 2	208
W-8a	Felix No. 1	209
W-9	Felix No. 2	252
W-10a	Felix No. 1	253
W-11	Felix No. 2	409
W-12	Felix No. 2	86
W-13	Felix No. 2	174
W-14b	Sand	154[a]
Hy-2	Felix No. 2	64[b]
P-2	Felix No. 2	33
M-1	Felix No. 1	616

[a]Completed after gasification.
[b]Inside the cavity.

Since the Hoe Creek No. 3 experiment shutdown, we sampled the ground water in the vicinity of the gasification zone five times, at 1 week, 2 weeks, 1 month, 2 months, and 3.5 months after gasification ended. (Our measured changes in hydraulic head are discussed elsewhere in this report.) Although the results of most of the laboratory analyses are not yet available, some interesting indications are apparent based on field analyses and laboratory measurement of early samples from W-10a and W-11.

The field analysis of phenols indicates that the ground-water contamination is worse in the Felix No. 1 aquifer than in Felix No. 2. For example, W-7 (Felix No. 2) is next to W-8a (Felix No. 1), and W-9 (Felix No. 2) is next to W-10a (Felix No. 1). The results of phenols analyses are shown in Table 2. This is perhaps because the hydraulic pressure of the Felix No. 1 aquifer is lower than that of Felix No. 2; hence the system pressure (pressure maintained in the burn cavity during gasification) can push water farther away from the cavity and cause a larger void space in the Felix No. 1 coal seam. This will make the product gases, which were lost to the formation, travel farther away from the cavity through the Felix No. 1.

On the basis of measurements at the first two Hoe Creek experiments, we conclude that, a few days after gasification has begun, electrical conductivity and the concentrations of Ca^{2+}, Mg^{2+}, Na^{+},

TABLE 2. Field analysis of phenols in W-7, W-8a, W-9, and W-10a.

Wells	Aquifer	Dec. 7, 1979 (ppb)	Jan. 23, 1980 (ppb)
W-7	Felix No. 2	2	12
W-8a	Felix No. 1	290	228
W-9	Felix No. 2	2	10
W-10a	Felix No. 1	120	20

and K^{+} increase in the ground water around the gasification zone. We believe the increases are caused by the carbon dioxide present in the product gas that has escaped into the formation. The carbon dioxide will dissolve in the ground water and lower the pH value. This may cause some minerals in the coal to dissolve. A plot of $[CO_2]$ vs $[Ca^{2+}]$ (Fig. 11) suggests that the concentrations of CO_2 and Ca^{2+} are indeed related.

The early data from wells W-10a and W-11 near Hoe Creek No. 3 are further evidence that dissolved CO_2 leads to an increase in Ca^{2+}, Mg^{2+}, etc. Water collected from W-10a two weeks after gasification shows a 40-fold increase in CO_2, and an increase in Ca^{2+} from 140 ppm (pregasification) to

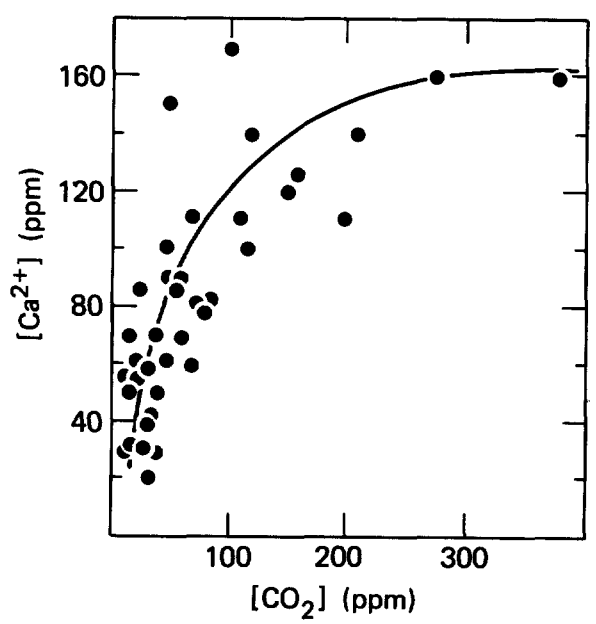

FIG. 11. Change of $[CA^{2+}]$ versus change of $[CO_2]$. The data were taken from wells EM-1, EM-4, EM-5, DW-4 (Hoe Creek No. 1), WS-5, WS-6, WS-7, and WS-8 (Hoe Creek No. 2). Before gasification, the average $[CA^{2+}]$ was approximately equal to 20 ppm and average $[CO_2]$ was approximately equal to 30 ppm.

310 ppm. By contrast, well W-11, approximately 400 ft from the injection well and nearly twice as far from the gasification cavity as is W-10a, shows no increase in CO_2 (compared with pregasification level) and also no increase in Ca^{2+}.

After the shutdown of gasification at Hoe Creek No. 3, ground water invaded the hot zone and steam was vented to the surface. We collected a steam sample and the steam contains approximately 2 ppm phenols, 1.5 ppm heterocyclic amines, and 0.5 ppm polycyclic aromatic hydrocarbons.

HYDROLOGIC EFFECTS RESULTING FROM AQUIFER INTERCONNECTION AT HOE CREEK NO. 2 AND NO. 3*

Our research project on ground-water hydrologic effects resulting from UCG experiments is designed, primarily, to evaluate the magnitude and extent of changes in hydraulic head and ground-water movement that result from aquifer interconnection. The gasified seam and two overlying aquifers appear to have been connected after roof collapse at both Hoe Creek No. 2 and No. 3. The evidence from postburn coring at Hoe Creek No. 2 indicates that the gasification cavity is connected through a permeable collapse zone with the Felix No. 1 coal aquifer and, probably, with the sand aquifer that overlies the Felix No. 1 (Fig. 12).[1] Field investigations before gasification established that hydraulic-head potential decreases with increasing depth at both sites.[2] Therefore, we expect that water from the overlying aquifers is flowing down through the collapse zone to the region of the gasification cavity, under the influence of the downward hydraulic gradient. It then flows into the Felix No. 2 coal, raising its hydraulic-head potential locally. It is important to understand the altered hydraulic regime and how it may affect contaminant dispersal. This understanding is imperative if we are going to design an effective environmental control technology.

To evaluate changes in the ground-water flow regime at the two sites, we completed supplementary wells and acquired hydraulic-head data. These activities are summarized below.

Hoe Creek No. 2

Three wells (WS-15, WS-16, and WS-17) were completed in the sand aquifer above the Felix No. 1 coal (see Fig. 13). We used these wells to locate the top of the zone of saturation (18 m below the local ground surface), but their primary purpose is to provide distance-head drawdown relationships in the sand aquifer. Note that gases trapped in the sand (presumably during gasification) were released while these wells were being drilled. Gas concentration increased with depth until the water table was reached. We obtained gas samples for analysis.

Relative well-head elevations and horizontal distances between new wells were measured so that distance-head drawdown curves could be plotted with time.

Hoe Creek No. 3

Well W-10a was constructed into the Felix No. 1 coal (see Fig. 14). This well, together with wells W-1a, W-4a, and W-8a, are being used to determine distance-head drawdown relationships in the Felix No. 1 coal.

Wells W-5b and W-14b were dug in the sand aquifer that rests on top of the Felix No. 1 coal at Hoe Creek No. 3. Preliminary hydraulic-head data from the lower aquifers suggested the importance of additional hydraulic information on the sand aquifer. A third well, closer to the gasification cavity, may be required at a later date. All of these wells will be used to study distance-head drawdown relationships. The top of the saturation zone has been determined to be 34.4 m below local ground level.

Relative well-head elevations and horizontal distances between all wells were measured so that distance-head drawdown curves could be plotted with time until some steady-state flow regime is achieved.

Hydraulic head has been measured in wells at Hoe Creek No. 3 since gasification ended on October 10, 1979. These data are plotted in Figs. 15-17.

---

*Support for these investigations is provided by the Ground-Water Research Branch (EPA/RSKERL) under grant No. EPA-IAG-79-D-X0795.

1. H. C. Ganow, "Post-Burn Coring Results," in *LLL In Situ Coal Gasification Quarterly Report, October through December, 1978*, R. W. Hill and K. J. Minkel, Eds., Lawrence Livermore Laboratory, Livermore, CA, UCRL-50026-78-4 (1979).
2. R. Stone and D. F. Snowberger, *Evaluation of the Native Hydraulic Characteristics of the Felix Coal and Associated Strata, Hoe Creek Site, Campbell County, Wyoming*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-51992 (1976).

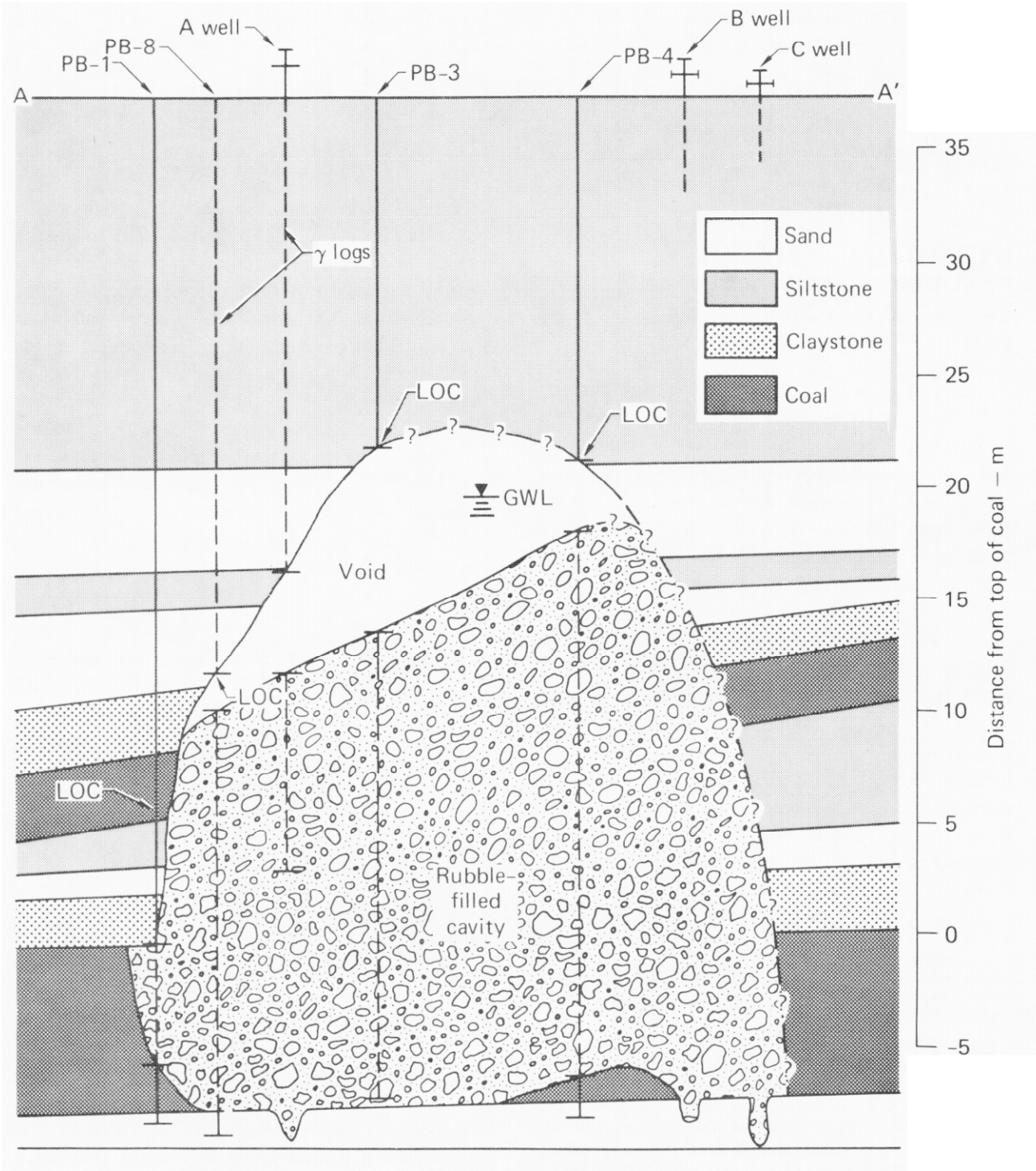

FIG. 12. Collapse-cavity section A-A′ at Hoe Creek Experiment No. 2.

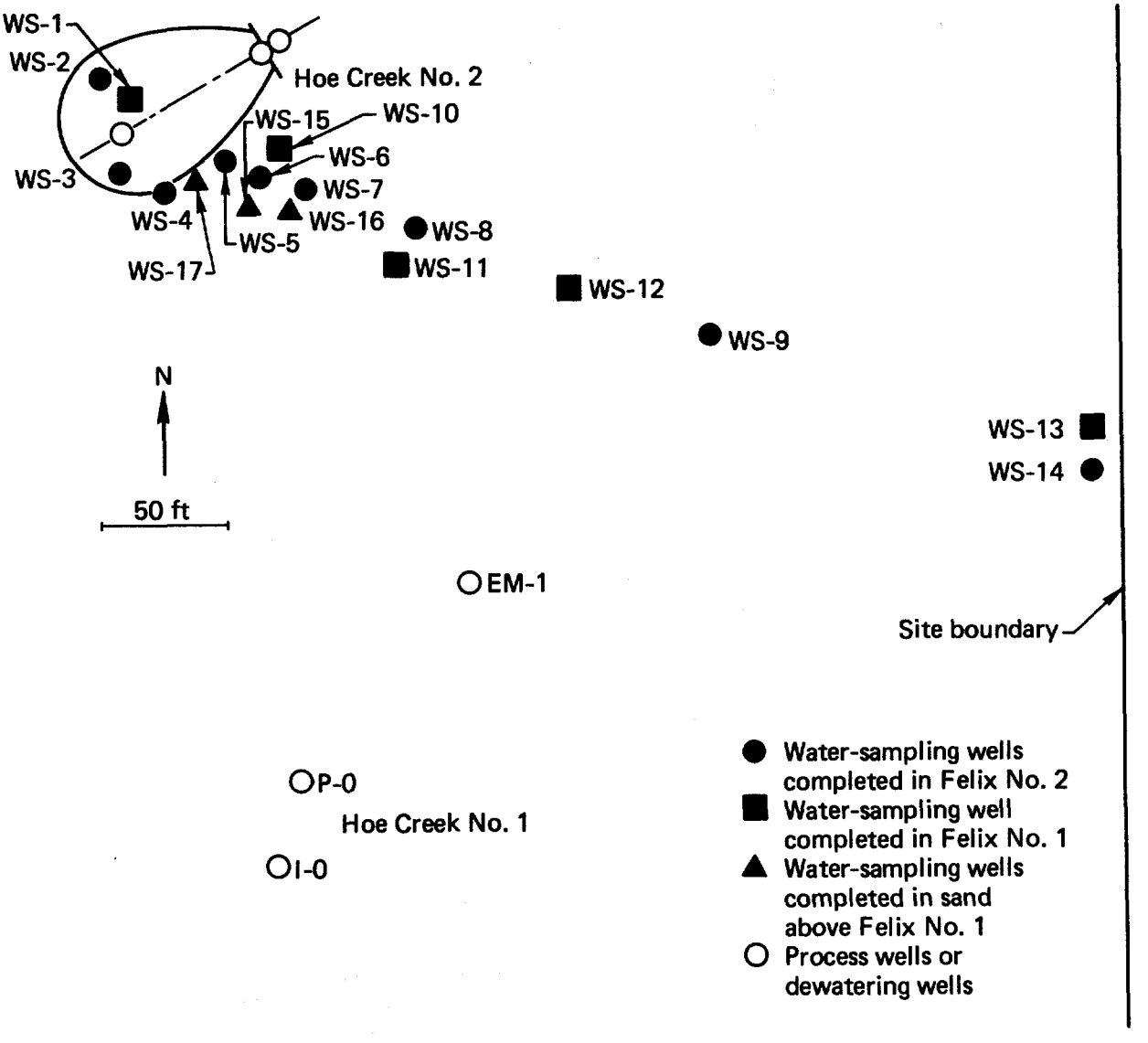

FIG. 13. Water sampling wells at Hoe Creek No. 2.

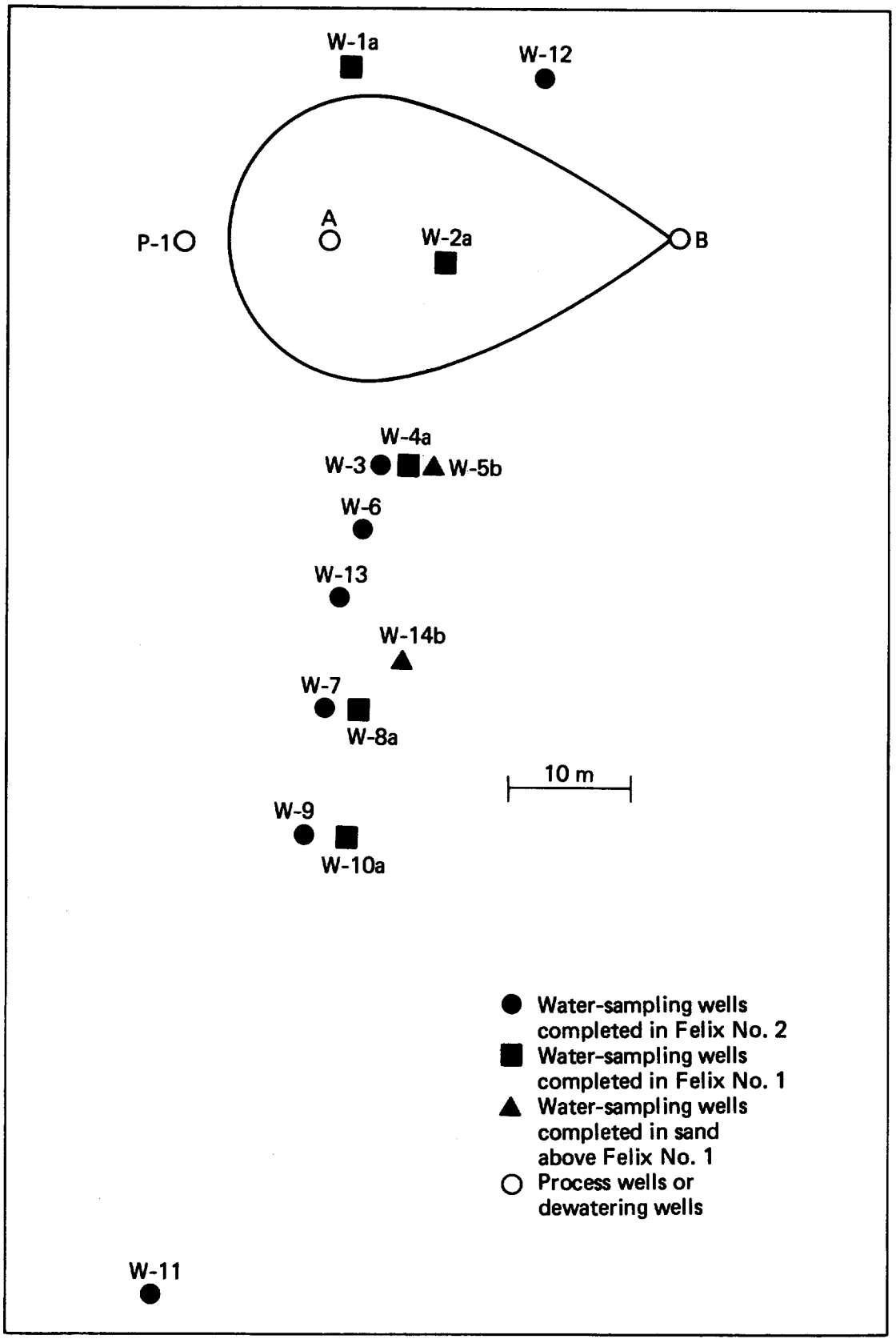

FIG. 14. Plan view of water sampling wells at Hoe Creek No. 3.

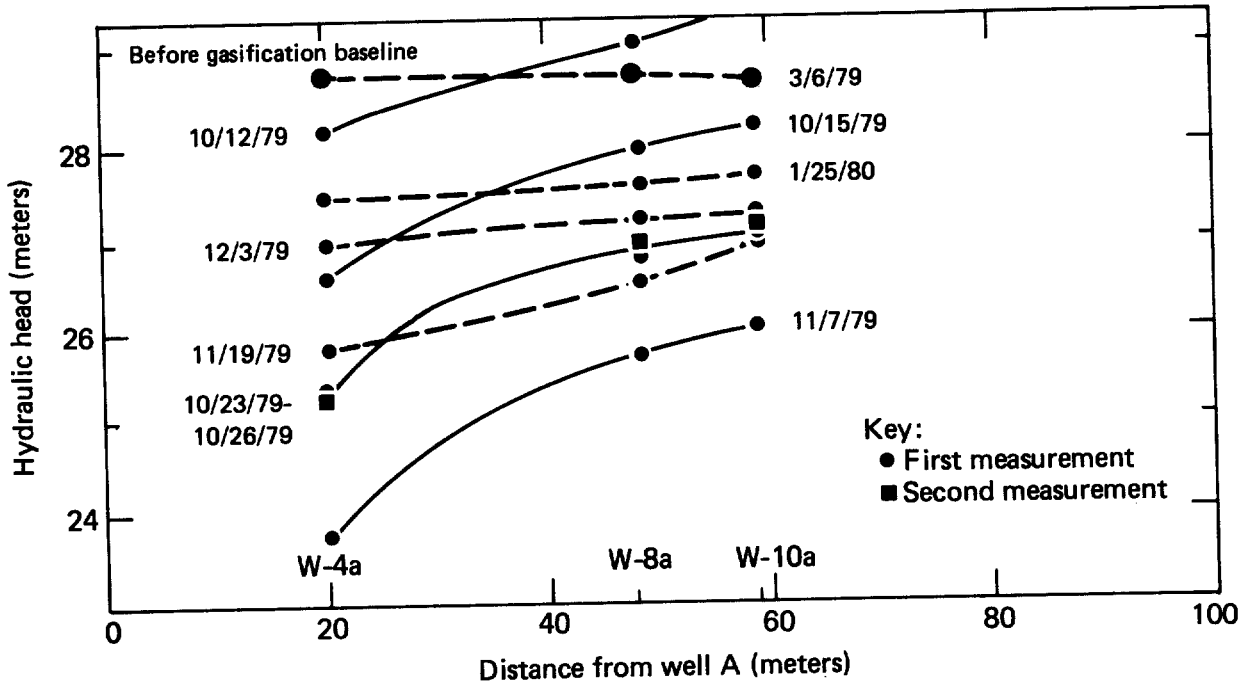

FIG. 15. Hoe Creek No. 3: Changes in hydraulic-head potential in the Felix No. 1 coal after gasification.

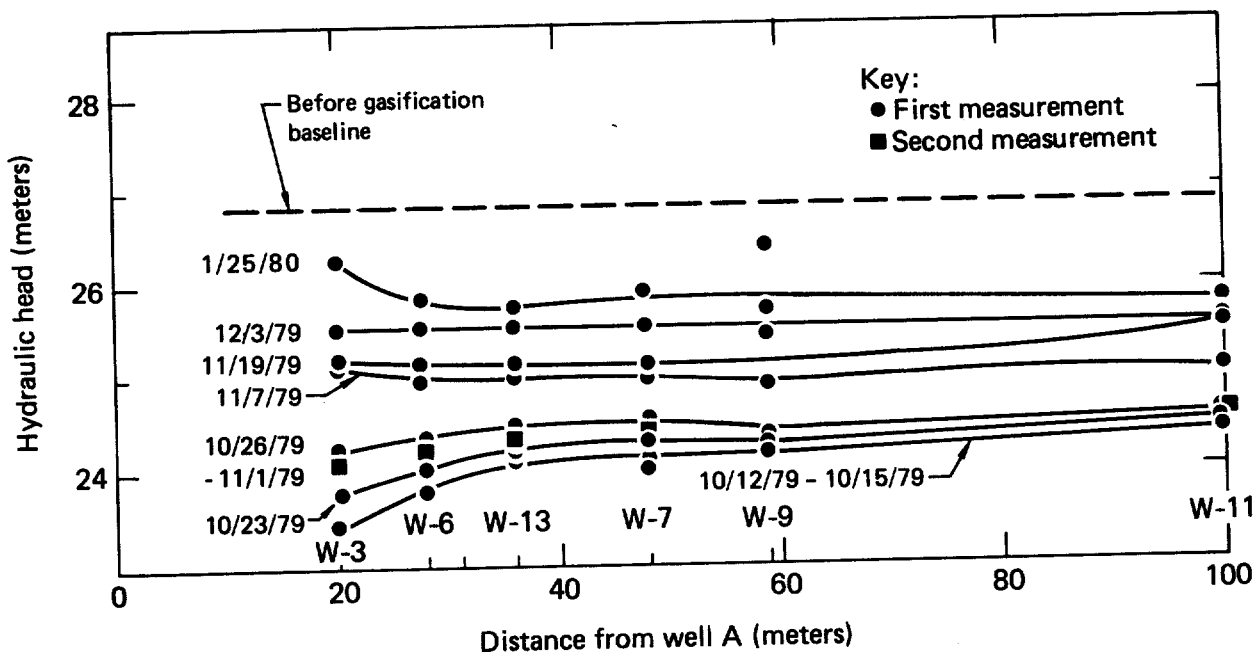

FIG. 16. Hoe Creek No. 3: Changes in hydraulic-head potential in the Felix No. 2 coal after gasification.

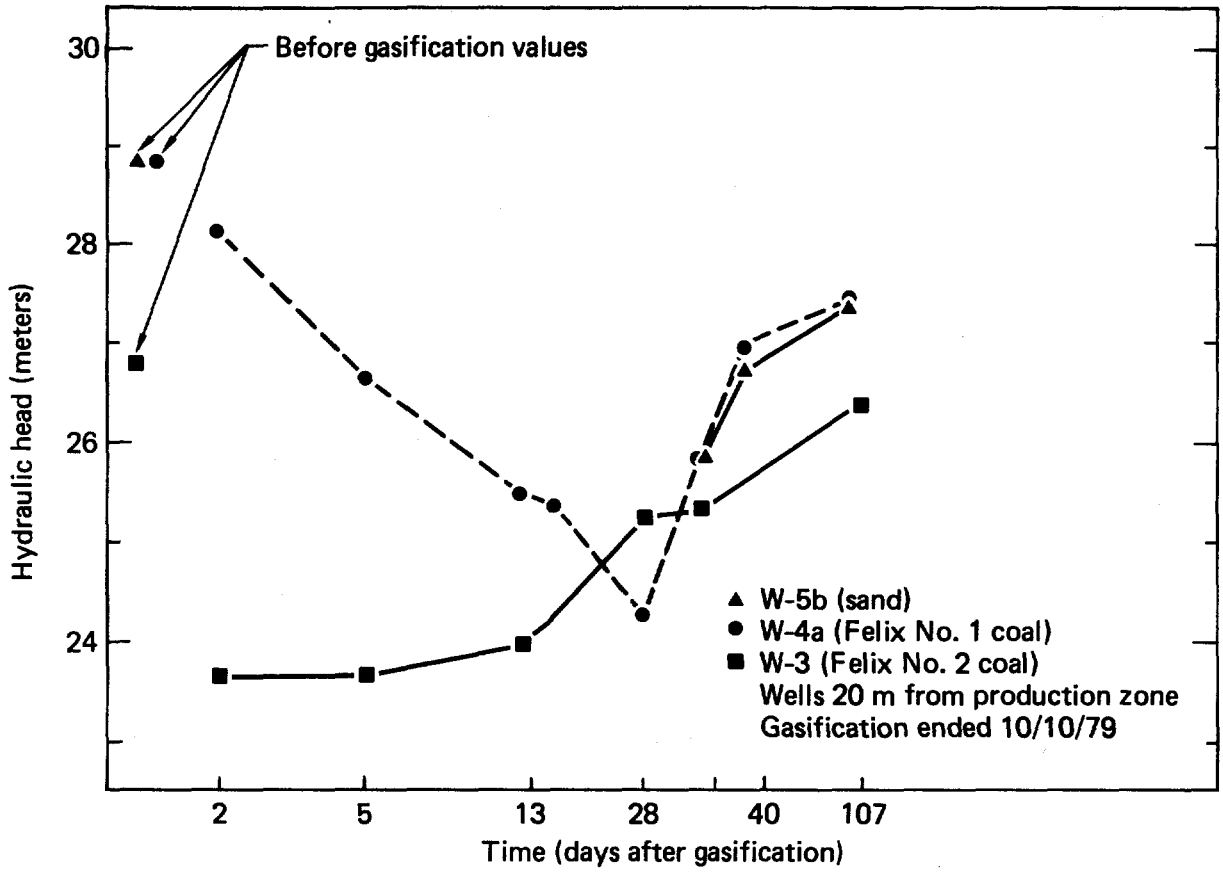

FIG. 17. Hoe Creek No. 3: Changes in hydraulic-head potentials with time after gasification.

The results (shown in Fig. 15) for the overlying Felix No. 1 coal represent a cone of depression centered at the gasification cavity. The curves approximate the parabolic form expected when water flow is removed from a point in an aquifer. In this case, water flows down through the collapse zone. Hydraulic-head potentials in the Felix No. 1 coal were decreasing with time until sometime after October 23, 1979. By November 19, 1979, however, hydraulic heads were increasing toward the pregasification baseline. Water levels in the two wells completed in the overlying sand aquifer indicate no hydraulic gradient. This suggests that a third well may be desirable, as previously mentioned.

The hydraulic-head potentials in the Felix No. 2 coal at Hoe Creek No. 3 can be seen in Fig. 16. After gasification, ground water flowed radially in towards the cavity until November 1, 1979. Measurements taken on November 7, 1979 show that the hydraulic-head potential was increasing near the cavity, indicating that radial flow away from the cavity had begun. This flow pattern is similar to that observed after the previous experiment at Hoe Creek No. 2. It should be noted that all hydraulic heads in the Felix No. 2 coal are still depressed, presumably because of a net water withdrawal from the aquifer during gasification. However, water levels in the Felix No. 2 coal are increasing toward pregasification baseline levels.

Figure 17 shows hydraulic-head changes in individual wells in each aquifer as a function of time. Wells W-5b (sand aquifer), W-4a (Felix No. 1 coal), and W-3 (Felix No. 2 coal) are within a few meters of each other and approximately equidistant from the gasification cavity. Briefly, this plot further shows that hydraulic-head potential increases in the Felix No. 2 coal with time. Conversely, the potential of the Felix No. 1 coal decreased until the hydraulic head in the Felix No. 2 reached a value such that the declining head trend was reversed. Ground water continues to flow into the cavity from the Felix No. 1, though under reduced hydraulic gradient. The hydraulic head in the sand aquifer seems to be following the same trend as that in the Felix No. 1 coal.

It was initially hoped that data obtained from Hoe Creek No. 2 and No. 3 would represent two independent altered hydrologic regimes. However, the gasification at No. 3 has significantly altered the ground-water flow patterns at No. 2. This can be seen in Figs. 7 and 8. Approximately 1.5 years after gasification, Hoe Creek No. 2 seemed to be approaching the steady-state condition shown in Figs. 18 and 19 (March 26, 1979). The hydraulic heads in both the Felix No. 1 and Felix No. 2 coals had remained fairly constant, with increasing potentials toward the gasification cavity. This implies that water from the overlying sand aquifer is flowing radially into both coal aquifers through cavity connections and that the direction of flow in both the Felix No. 1 and Felix No. 2 aquifers is away from the collapse zone.

However, near the end of gasification at Hoe Creek No. 3, after the roof collapsed and the overlying aquifers interconnected (October 10, 1979), the hydraulic-head values at No. 2 were quite different. The gaseous back pressure at No. 3 caused the

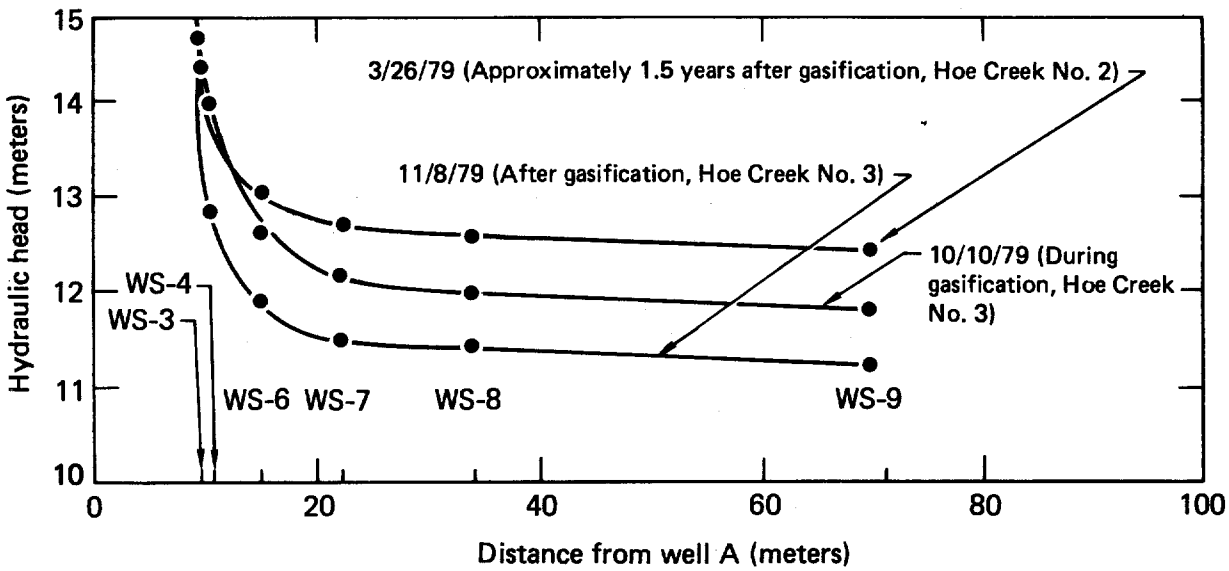

FIG. 18. Hoe Creek No. 2: Hydraulic-head changes in Felix No. 2 coal.

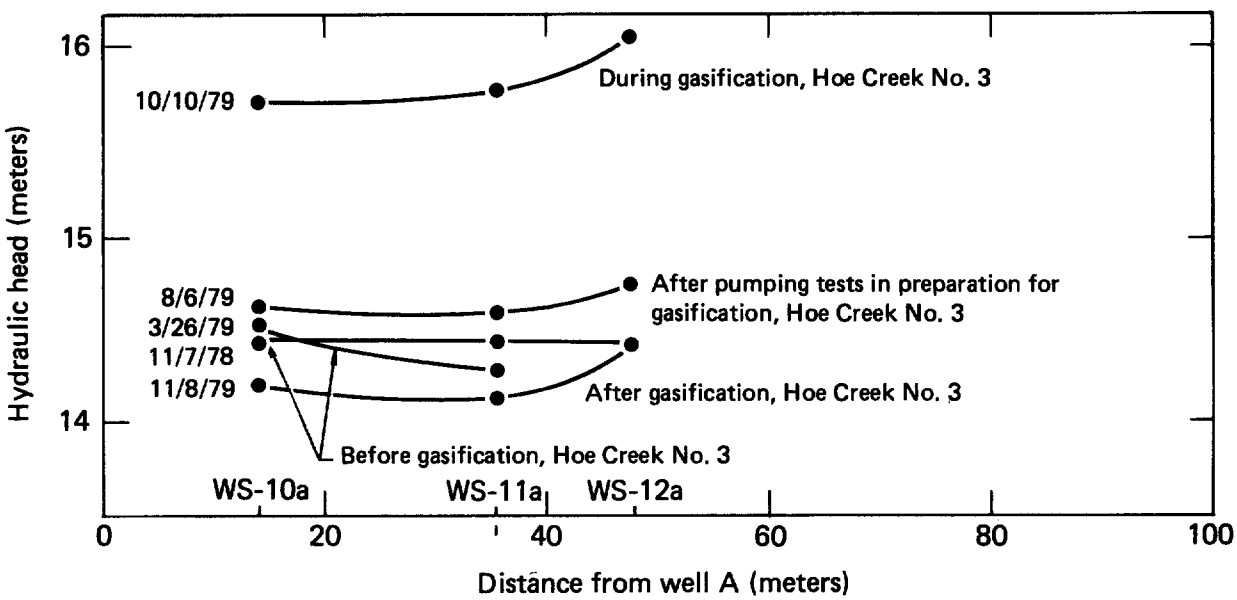

FIG. 19. Hoe Creek No. 2: Hydraulic-head changes in Felix No. 1 coal.

hydraulic head of the Felix No. 1 coal to rise substantially and changed the hydraulic potential gradient such that flow is now toward and into the cavity at Hoe Creek No. 2. The additional flow from the Felix No. 1 coal aquifer through the collapse zone and into the Felix No. 2 at Hoe Creek No. 2 caused a much steeper hydraulic gradient in the Felix No. 2, with head potentials decreasing away from the cavity as before. Therefore, the ground-water flow direction was still away from the cavity, although the overall head of the Felix No. 2 was depressed. This appears to be caused by the net water withdrawal from the aquifer during gasification at Hoe Creek No. 3, which created a cone of depression extending to Hoe Creek No. 2. Wells had not been drilled into the overlying sand aquifer at this time.

After gasification at Hoe Creek No. 3 ended, the water level was measured (November 8, 1979) at Hoe Creek No. 2. The hydraulic gradient in the Felix No. 1 coal indicates that radial flow is still toward and into the gasification cavity. Because the gaseous back pressure from Hoe Creek No. 3 has been relieved, the overall hydraulic head in the Felix No. 1 is lower and probably will remain so until steady-state conditions in all interconnected aquifers are reestablished. After gasification, the Felix No. 2 coal at Hoe Creek No. 2 still shows a steeper hydraulic gradient away from the cavity than initially was present.

Ground-water flow is still radially away from the collapsed cavity in the Felix No. 2 coal. The overall hydraulic head in the Felix No. 2 is lowest immediately following the end of gasification at Hoe Creek No. 3. This is explained by the net water withdrawal from the aquifer and the absence of gaseous back pressure, which cause a reduced flow from the overlying Felix No. 1 aquifer into the Felix No. 2.

These changes at Hoe Creek No. 2 will definitely affect contaminant dispersal and should be taken into consideration. These two experiments are no longer separate, and at this point cannot be considered independently. No doubt Hoe Creek No. 1 has also been influenced by these two later experiments. This brief summary represents the first steps in our efforts to completely describe the altered hydrologic regime caused by aquifer interconnection.

DEEP 1 EXPERIMENT

INVESTIGATION OF POTENTIAL UCG SITES IN WYOMING

Exploratory wells were drilled at two sites in the Powder River Basin near Gillette, Wyoming. Some hydraulic characteristics of the coal seam of interest were evaluated at one site. The first work was at the Hoe Creek site where the Roland coal at about 130 m (422 ft) depth was the seam of interest. The second site explored is the Wildcat Creek lead, located in Section 21, T52N, R73W, about 26 km (16 mi) northwest of Gillette. The Canyon coal at about 180 m (590 ft) depth is the seam of interest at the Wildcat Creek lead. The seams of interest at both sites are contained in the Paleocene Ft. Union Formation.

Hoe Creek Site

A borehole was drilled to a total depth of 128.6 m (422 ft) at the Hoe Creek site. The lower 30 m (98 ft) of the borehole was cored with conventional techniques. The natural gamma radiation and bulk density of the strata penetrated were measured and logged with our borehole geophysical logging equipment. Figure 20 illustrates the sequence of strata encountered in the Hoe Creek deep exploratory well. This stratigraphic section is based on descriptions of drill cuttings and core, and on the borehole geophysical measurements. Drilling was carried to a point a short distance above the top of the Roland coal seam where casing was set and cemented as a prelude to further testing. The depth to the top of the Roland seam was known from previous exploratory drilling at the Hoe Creek site.

A 17-m (56-ft) thick sequence of sandstone was found above the Roland seam. This sequence is separated from the top of the Roland by only about 3.5 m (11.5 ft) of claystone. The sandstone is fine- to medium-grained and is unindurated to slightly indurated. Examining the sandstone led us to conclude that it has the hydraulic properties of an aquifer. Our own experience and that of others[3] has shown that underground gasification of a coal seam closely overlain by an aquifer is difficult, if not impossible. Therefore the Roland coal at the Hoe Creek site was rejected as a reasonable seam in which to plan an underground gasification test.

Wildcat Creek Lead

A borehole was drilled 181 m (595 ft) deep at the Wildcat Creek lead. At that depth, about 2.5 m (8 ft) into the top of the Canyon coal seam, steel casing was set and cemented in place. The casing was set into the seam to avoid the possibility of producing natural gas from the upper portion of the seam and its overburden. Further drilling then deepened the well into the Canyon seam in four increments. Hydraulic slug-withdrawal tests were performed in the well at each stage of deepening. After the slug tests, the well was drilled into the strata below the Canyon seam to a total depth of 207.3 m (680 ft). The well was then plugged back with cement to a point about 3 m (10 ft) below the base of the Canyon seam. A polyvinyl chloride well screen with 1 mm slot widths was installed and a submersible pump was placed at 122 m (400 ft) depth. Two pumping tests were performed. The details of construction of the Wildcat Creek exploratory well are illustrated in Fig. 21.

Information from logs of conventional core and drill cuttings together with that from natural gamma, bulk density, and self potential-resistivity logs of the Wildcat Creek exploratory well was combined to yield a description of the sequence of strata penetrated by the well. Figure 22 illustrates this sequence. The overburden cored above both Anderson and Canyon seams was mostly moderately indurated and hence reasonably competent. Selected core samples from the interval cored above the Anderson seam and from the cored interval above and below the Canyon seam, as shown in Fig. 22, were preserved to retain their original moisture content. These samples are available for strength determinations.

The only aquifer for 60 m (196 ft) above the Anderson seam is the Smith seam. The first 60 m (196 ft) of overburden above the Canyon seam is free of aquifers. The strata immediately beneath the Anderson seam, though not cored, do not appear to harbor an aquifer. The same cannot be said about strata beneath the Canyon seam. The predominant lithology penetrated in the 10 m (33 ft) of hole

3. R. F. Strickland and J. W. Jennings, "Analysis of Geologic Limitations to Underground Coal Gasification," *In Situ* 3(3), 209–226 (1979).

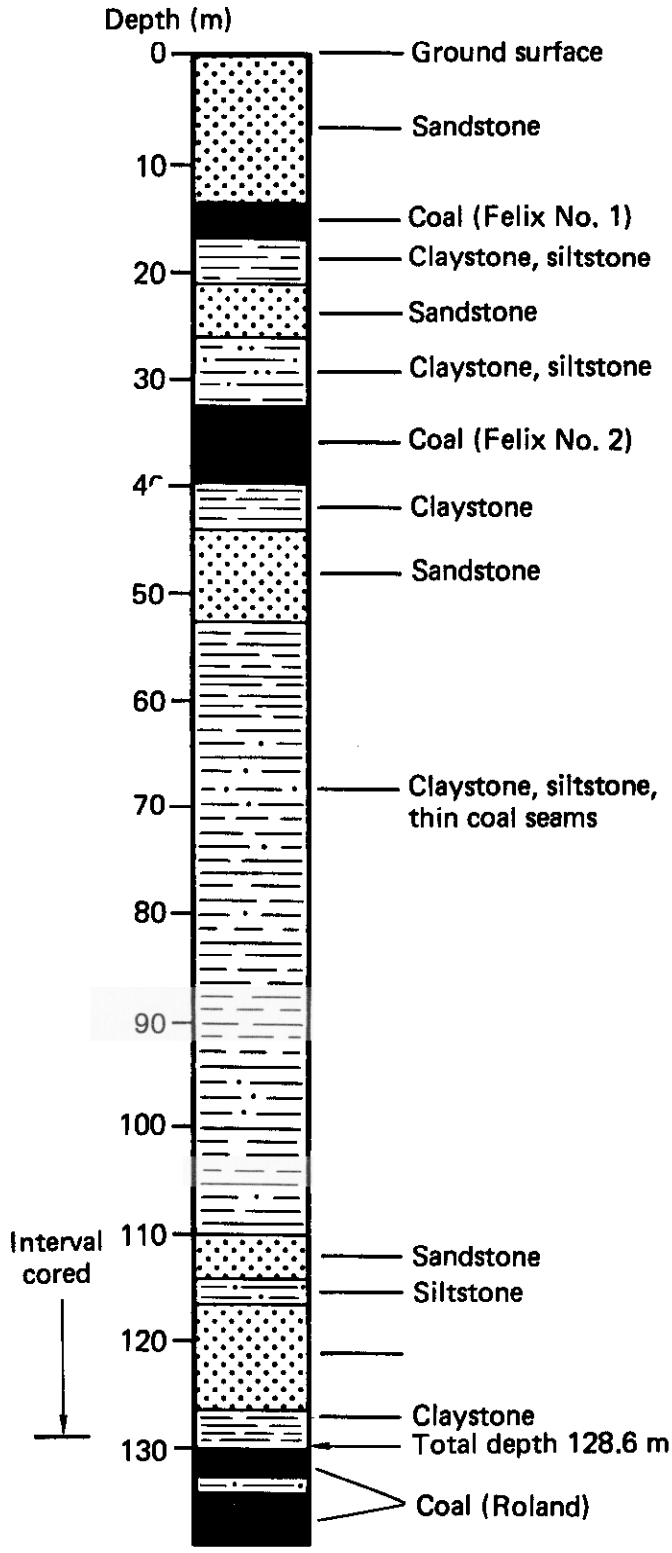

FIG. 20. Strata encountered in drilling Hoe Creek deep exploratory well No. 4.

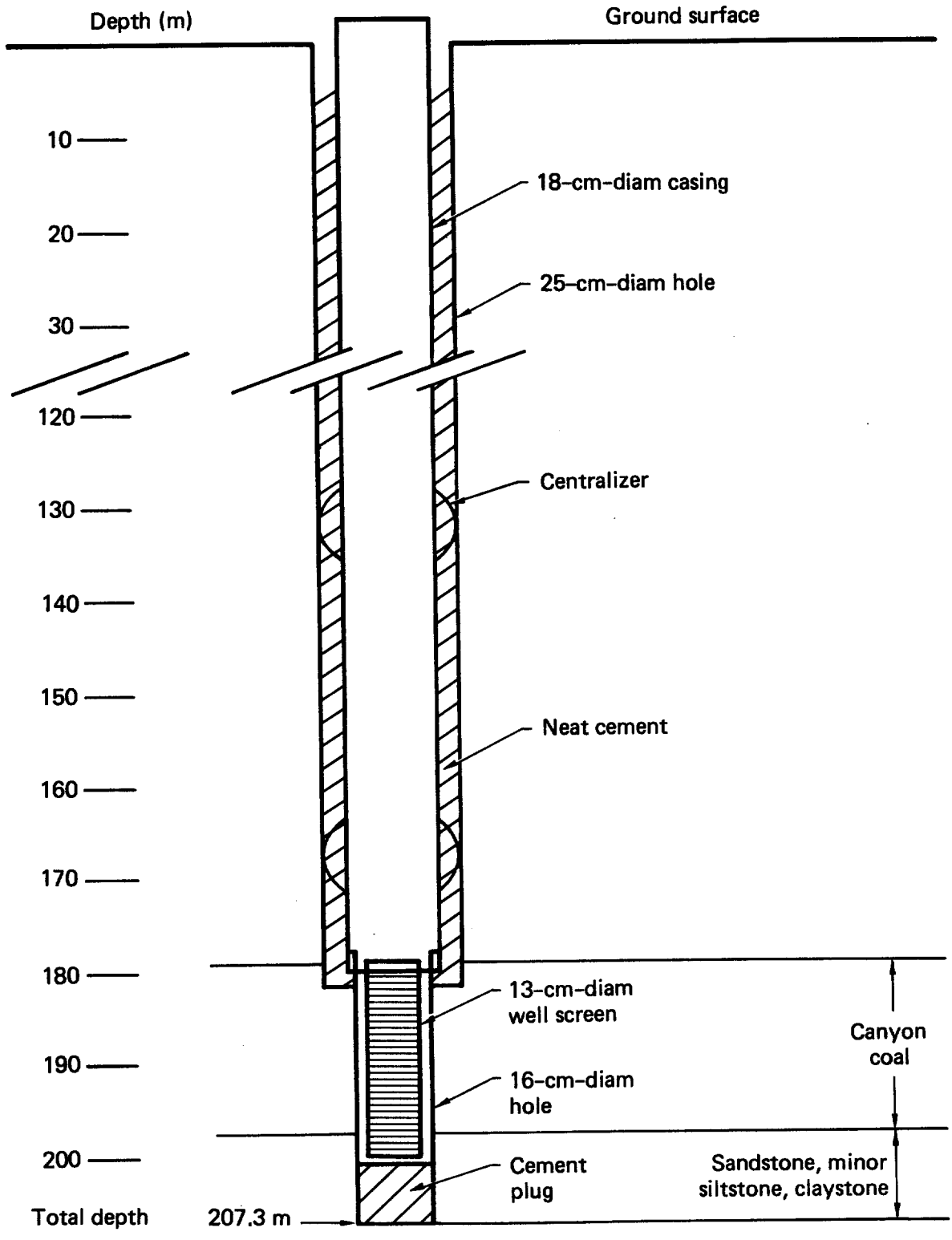

FIG. 21. Construction detail of the Wildcat Creek exploratory well.

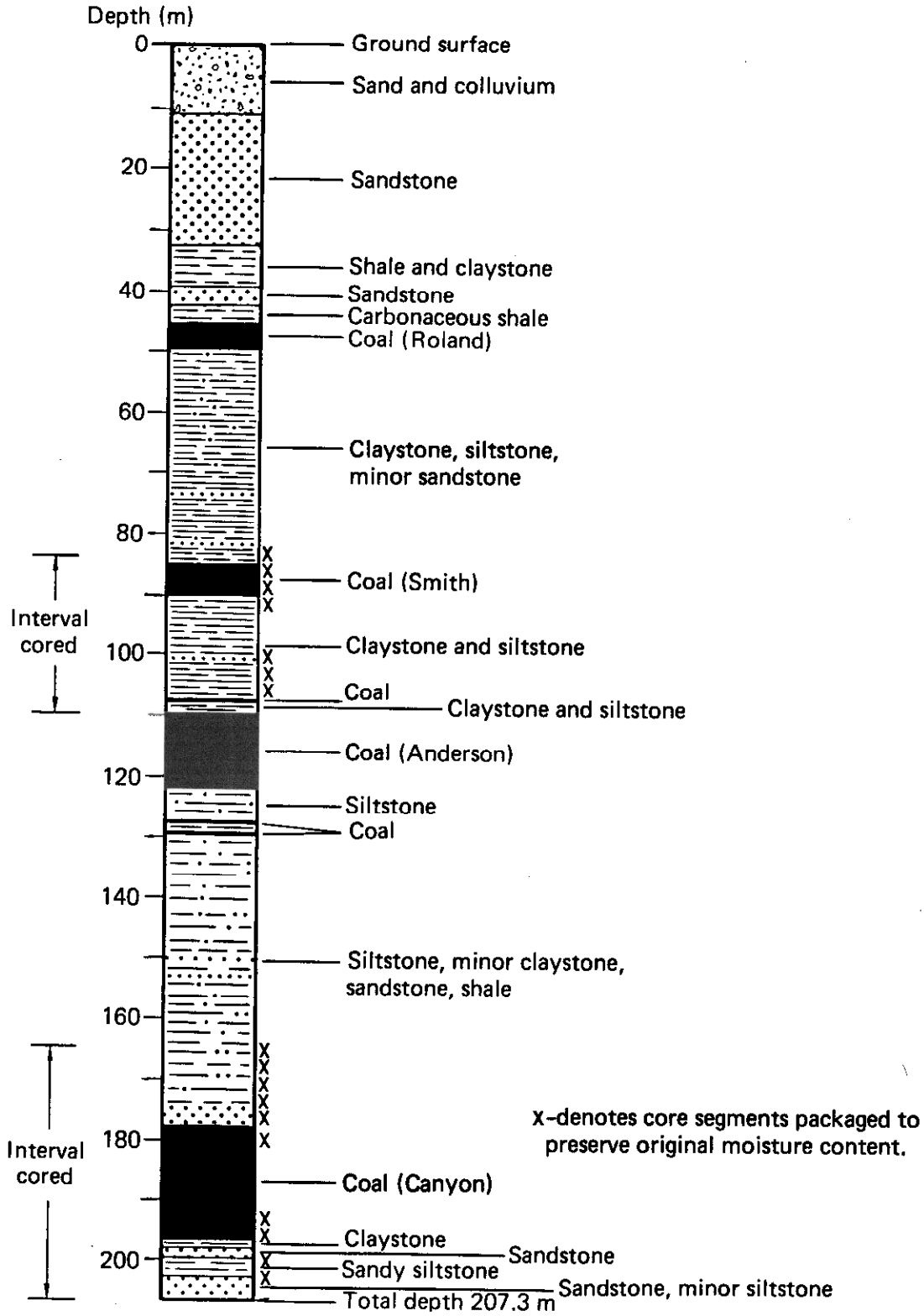

FIG. 22. Strata encountered in drilling Wildcat Creek exploratory well.

TABLE 3. Analysis of Canyon coal from Wildcat Creek lead.

Proximate analysis, %			Ultimate analysis, %			Sulfur forms, %		
	As received	Dry basis		As received	Dry basis		As received	Dry basis
Moisture	28.75	–	Moisture	28.75	–	Pyritic	0.03	0.04
Ash	4.70	6.59	Carbon	51.03	71.62	Sulfate	0.00	0.00
Volatiles	30.99	43.49	Hydrogen	3.46	4.85	Organic (diff)	0.22	0.31
Fixed carbon	35.56	49.92	Nitrogen	0.94	1.32	Total	0.25	0.35
Total	100.00	100.00	Chlorine	0.06	0.08			
Sulfur	0.25	0.35	Sulfur	0.25	0.35			
BTU (per lb)	8826	12388	Ash	4.70	6.59			
			Oxygen (diff)	10.81	15.19			
			Total	100.00	100.00			

drilled below the Canyon is sandstone. This sandstone varies from unindurated to moderately indurated. Its dominant grain size varies from fine to coarse. The sandstone below the Canyon seam is presumed to be an aquifer.

Three coal samples from the Canyon seam (Fig. 22) were combined and subjected to standard coal analysis. Table 3 contains the results of the analysis. The Canyon is a low-ash, low-sulfur, subbituminous coal.

The incremental slug-withdrawal tests, performed in the Wildcat Creek exploratory well as it was deepened into the Canyon seam, were conducted and interpreted according to procedures previously described.[4] Water was rapidly removed from the well by air-lift pumping; the rig drill pipe was used as the air-injection line. Columns of water ranging from about 15 to 30 m (50 to 100 ft) high were withdrawn from the cased well in this manner.

The water-level recovery of one of the four slug-withdrawal tests is illustrated in Fig. 23. The test was initiated by rapidly removing a column of water 14 m (46 ft) high from the well. The measured recovery was 90% complete in 27 min. Analysis of the four slug-withdrawal tests indicates that a lower portion of the Canyon seam is the most permeable. Table 4 summarizes the slug test results. The lowermost 2 m (6 ft) of the Canyon apparently has negligible permeability. This correlates well with the fact that the core of the lowermost 1.5 m (4 ft) of the seam displayed poor fracture development.

4. R. Stone, *Measurement of the Spatial Variation of Hydraulic Characteristics of an Explosion-Fractured Coal Seam*, Lawrence Livermore Laboratory, Livermore, CA, UCRL-52298 (1977).

The overall permeability of the Canyon seam is not much different from that of the Felix No. 2 coal at Hoe Creek. The Canyon is 2.5 times thicker than the Felix No. 2 however, so its transmissivity is correspondingly greater. The static water level in the Wildcat Creek exploratory well is about 67 m (220 ft) below the surface. Therefore, about 113 m (370 ft) of artesian head exists above the top of the Canyon seam. Only about 15 m (50 ft) of head exists above the top of the Felix No. 2 at Hoe Creek. Thus, much more water could be produced from a well completed in the Canyon seam because of its greater transmissivity and greater available drawdown.

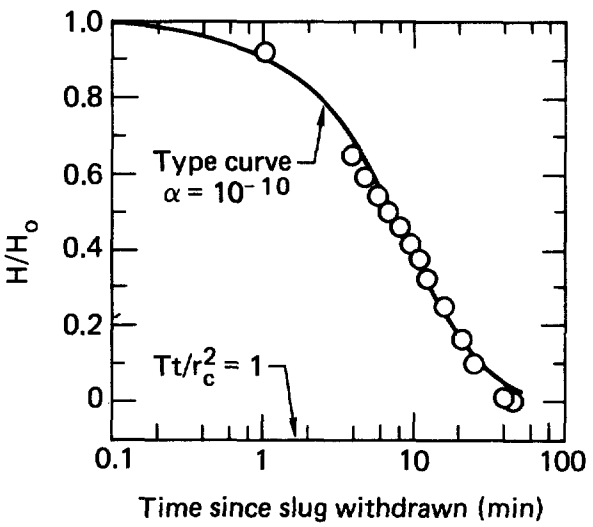

FIG. 23. Water-level recovery in second slug-withdrawal test in Wildcat Creek exploratory well. The interval tested was 181–191 m.

TABLE 4. Estimated horizontal intrinsic permeability of Canyon seam, Wildcat Creek lead.[a]

Depth interval, m (ft)	Interval thickness, m (ft)	Intrinsic permeability, $(\mu m)^2$
Top Canyon seam 179 m (587 ft)		
181–186 (595–610)	5 (15)	0.33
186–191 (610–626)	5 (16)	0.99
191–196 (626–642)	5 (16)	2.10
196–199 (642–652)	3 (10)	Negligible
Bottom Canyon seam 198 m (649 ft)		
181–196 (595–642) (essentially full seam)	15 (47)	1.15

[a]Based on single-well, slug-withdrawal tests.

The equilibrium water levels measured before each of the four slug-withdrawal tests show a trend: hydraulic-head potential increases with depth, at least through the Canyon seam and into the first 1 m (3 ft) of underlying strata. The equilibrium water level measured before the second pumping test of the well, when it had been screened to a point 3 m (10 ft) below the base of the Canyon, also indicates that head increases with depth.

After the Wildcat Creek exploratory well had been completed (final configuration shown in Fig. 21), two pumping tests were performed on the well. Neither test led to credible estimates of hydraulic characteristics of the Canyon seam, probably because of turbulent flow in fractures near the well bore. Permeability estimates from the pump tests are about one-tenth those determined from the results of slug-testing the well. These results are at odds with the observed rapid recoveries from slug testing and with the estimated maximum yield of the well.

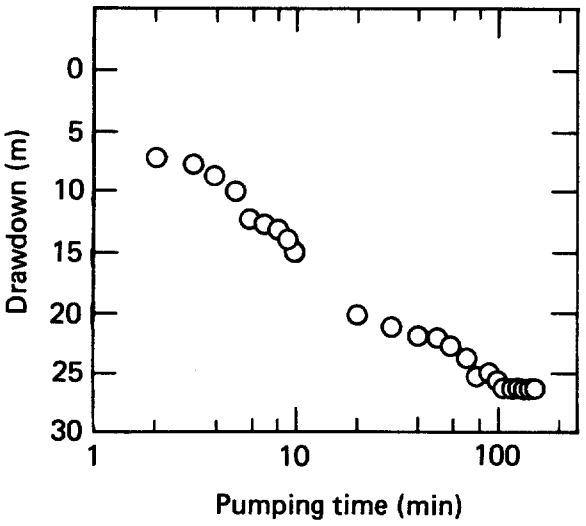

FIG. 24. Drawdown in Wildcat Creek exploratory well resulting from pumping at 106 m^3/day.

The drawdown histories from the two pumping tests are of interest however, because they illustrate that quasi-steady pumping water levels were established after rather short pumping times. Figure 24 shows the drawdown in the Wildcat Creek exploratory well during the second pumping test. The cessation of drawdown at about 100 min is taken as an indication of leakage into the Canyon seam. Leakage from above the seam is not favored because siltstone predominates in the overburden. Leakage from below is favored by the higher hydraulic-head potential of the sandstone underburden. As the well is constructed, some leakage can occur upward through the screened section because the well is screened into about 2 m (6.5 ft) of sandstone below the Canyon seam.

Some entrained methane was noted in the water brought to the surface in the first pump test. The water pumped to the surface in the second test ran clear, however, and apparently carried much less methane.

The quasi-steady drawdown during the second pump test was 25 m (85 ft). Based on this drawdown and the constant discharge, 106 m^3/day (19.4 gpm), the specific yield of the well is 4.2 m^3/day per meter of drawdown (0.23 gpm per foot of drawdown). With its available drawdown of about 113 m (370 ft) the well could produce about 475 m^3/day (85 gpm). Even if one makes the reasonable assumption that one tenth of this production would come from the 2 m (6.5 ft) of sandstone below the Canyon, the coal seam would still produce about 427 m^3/day (76 gpm).

Summary

The Roland coal seam at the Hoe Creek site was rejected as a reasonable seam in which to plan an underground gasification test because it was found to be closely overlain by a thick sandstone aquifer.

The overburden above both the Anderson and Canyon seams at the Wildcat Creek lead has no aquifers for a substantial distance and is reasonably competent. The strata immediately beneath the Anderson seam do not appear to harbor an aquifer. Strata immediately beneath the Canyon are dominantly sandstone units that are water-bearing. The Canyon seam itself is a fair aquifer.

The Anderson seam at Wildcat Creek may be a fair seam for underground gasification if collapse to the surface following an experiment could be shown to be unlikely or an acceptable risk. The Anderson was not hydraulically tested, but we presume it is a fair aquifer.

The Canyon seam at the Wildcat Creek lead may be a fair seam for underground gasification. Only the upper 15 m (50 ft) of the seam should be gasified. The lower 3 m (10 ft) should be left as a seal against water intrusion and leakage from the sandstone below. Further testing to better establish the effectiveness of the 3 m (10 ft) coal seal should be done before any attempt to gasify the Canyon seam.

PRELIMINARY PLAN FOR THE DEEP 1 EXPERIMENT

Three experiments have now been completed in the Felix coal seams at Hoe Creek. Although the test results were encouraging, there are many uncertainties remaining that need clarification before underground coal gasification can be commercialized.

The main technical questions concern burn cavity growth, linking channel growth, the effects of overburden collapse, and repeatability of results. How these questions are affected by flow rate, coal type, or linking method is still not well understood.

In order to provide maximum support to the DOE program, we want to attempt to answer as many of these questions as possible.

We are proposing a field experiment, at Deep 1, at a new site in a coal seam at a commercially realistic depth. We propose an experiment to test cavity development with different flow ranges and different techniques for completing wells.

The major goals of Deep 1 are:

1. To study the development of a burn cavity using oxygen-steam injection.
2. To isolate the burn cavity from injection and production wells as much as possible.
3. To ensure that the injection point remains at the bottom of the coal seam during the entire forward burn.
4. To study the effects of gas flow rate on a drilled channel.
5. To study particulate production as a function of flow rate and time during the burn.
6. To determine what new problems occur when gasifying coal at a depth suitable for commercial development.
7. To investigate ways to protect the injection system during the early stages of forward burn.
8. To study burn-cavity formation as a function of flow rate and injectant composition.
9. To measure the ultimate burn width and average gas composition for economic analysis.
10. To continue the study of the environmental consequences of *in situ* gasification at a new site.

During most of the Hoe Creek No. 2 experiment, we were able to maintain the injection point at the bottom of the coal seam. This appeared to strongly influence cavity development and the quality of the gas produced. Both injection wells were damaged in the Hoe Creek No. 3 experiment and, although we were apparently successful in injecting into the Felix No. 2 coal seam, we were not able to maintain a low-seam injection point. The design proposed will allow us to test the importance of the position of the oxygen injection point by ensuring that the injection point remains at the bottom of the seam.

The basic design of the experiment to be called Deep 1 is illustrated in Figs. 25-27.

A directionally drilled hole is used as both an injection well and the linking channel. The hole is to be drilled so that it comes as close as possible to the floor of the coal seam and then continues horizontally along the bottom of the seam for 120 m (400 ft), or as far as possible. The hole is then cased and cemented except for the last 90 m (300 ft) in the coal seam. The oxygen lance will be inserted into the cased portion. The goal will be to come as close to the seam floor as possible so that the cement grout will be protected from breakage during the burn by touching the floor. The horizontal cased portion will provide a test of a scheme to protect against corrosion and also allow for considerable horizontal growth if the casing burns off. Thermocouple and high-frequency electromagnetic (HFEM) diagnostic instrumentation as well as water sampling well locations are shown in the figures.

Assuming that we are successful in constructing the experiment as planned, it will be necessary to protect the injection system from slag plugging by providing backups for both oxygen and steam systems. A low-capacity air evaporator for the oxygen system and a standby air compressor with an automatic valve for the steam system should be sufficient.

The main production well (C) is at the end of the uncased portion of the directionally drilled hole.

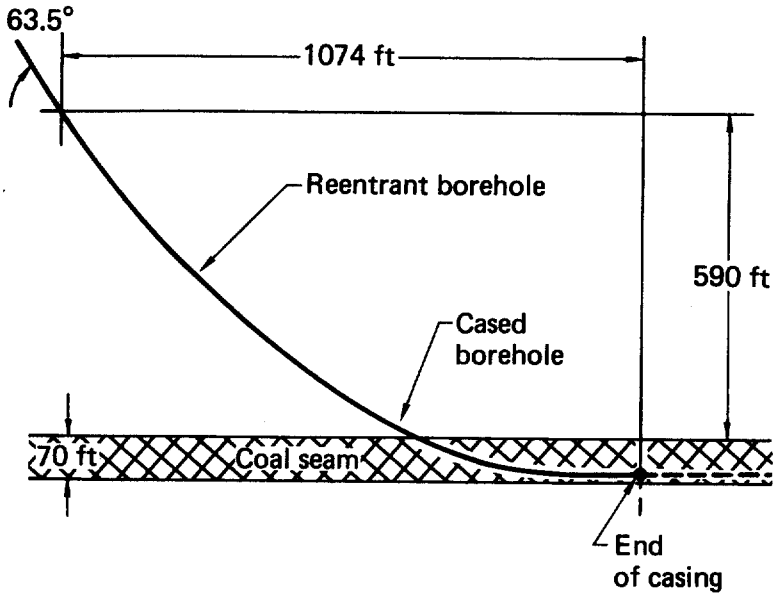

FIG. 25. Basic design of the experiment, Deep 1.

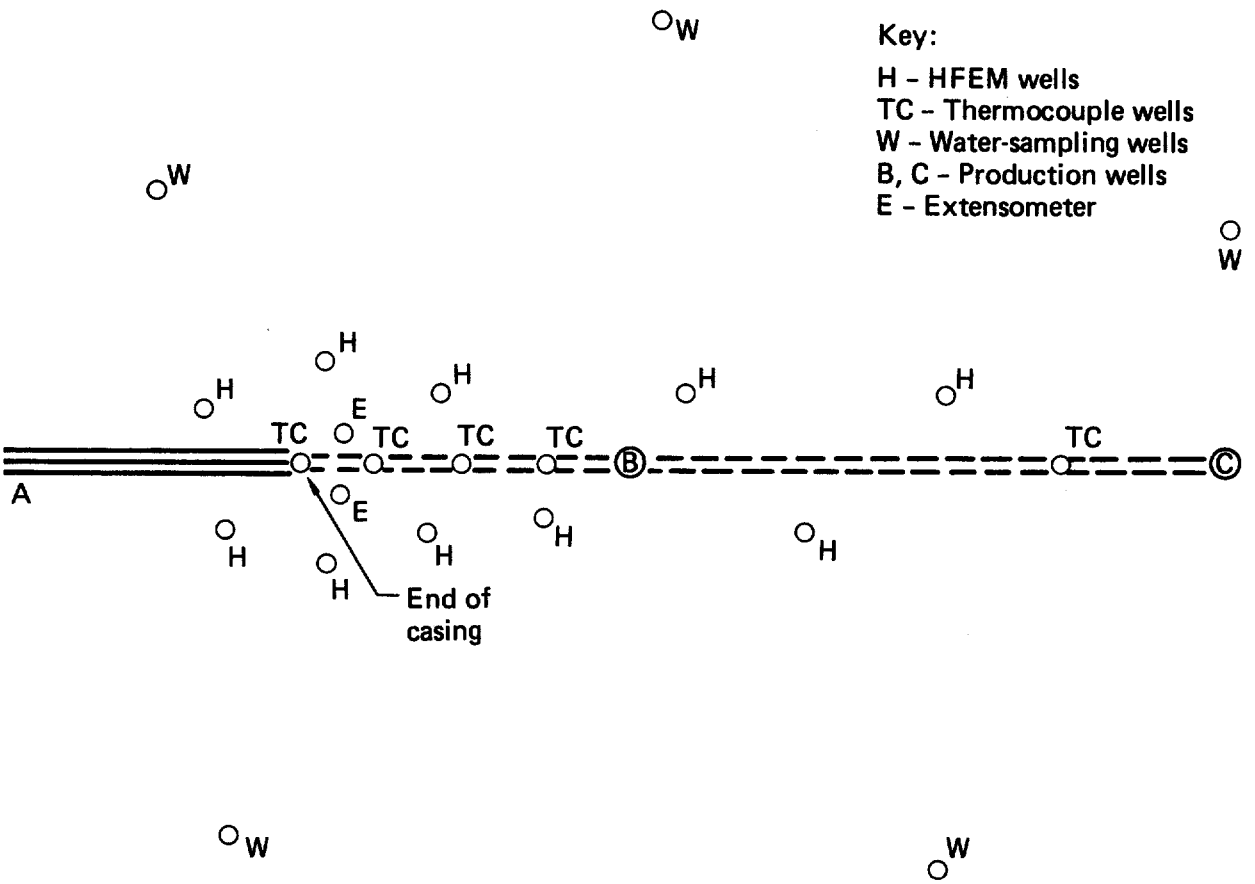

FIG. 26. Plan view of Deep 1.

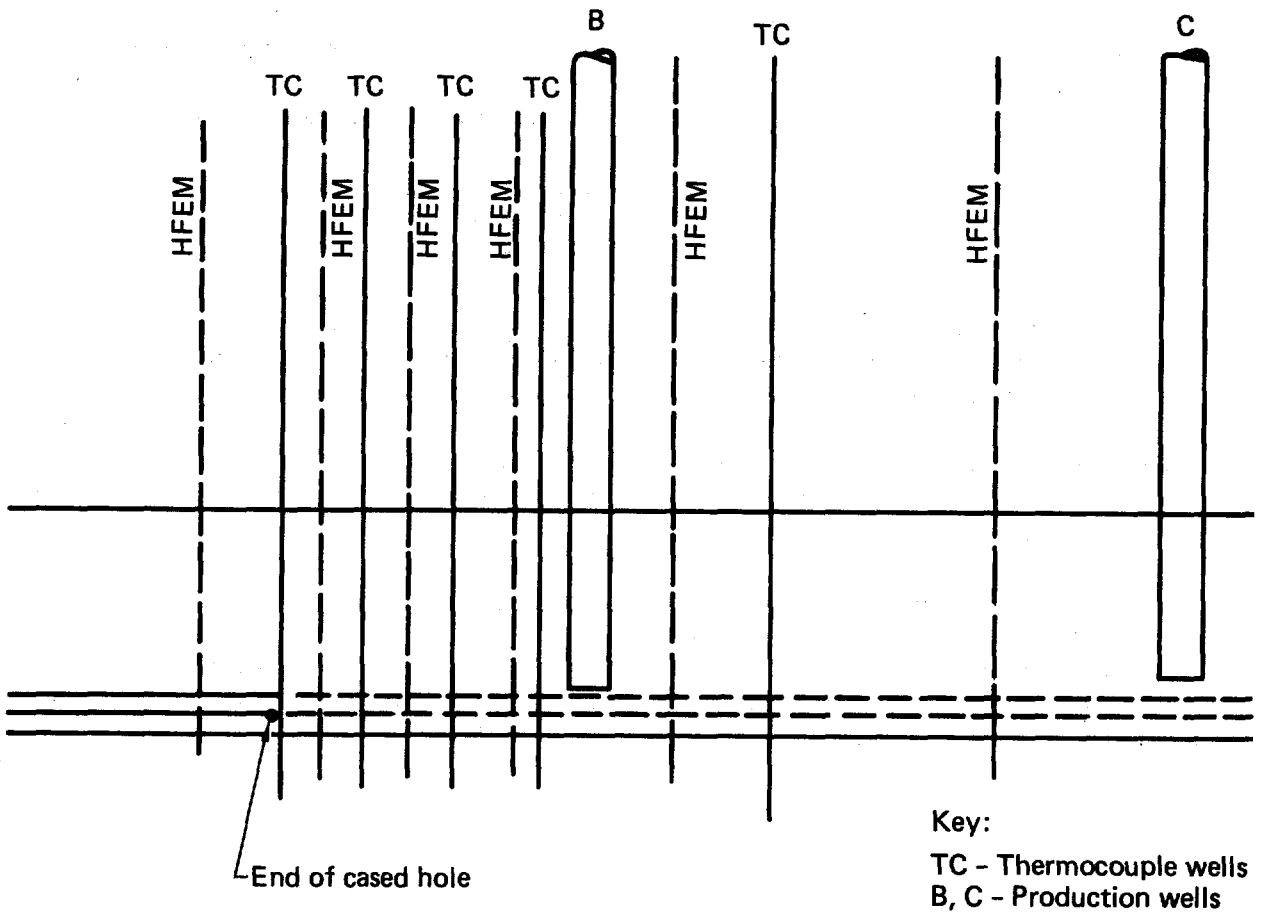

FIG. 27. Elevation of Deep 1.

A 90-m- (300-ft-) long production channel should adequately protect the well from the effects of cavity collapse and perhaps cool the gas sufficiently to reduce the heat load on the production well casing. The results from Hoe Creek No. 3 indicate that the casing survived, essentially intact, until the end of the experiment, although the cement bond did leak a bit; some design changes seem indicated.

Well B is designed as an auxiliary or production well. We hope it will not be used at all. However, it should be designed to be used either as an injection or production well, as needed.

Both wells B and C will be linked to the drilled channel by reverse combustion with air injection in A and ignition separately at the base of B and C. The C link will be completed first, with the fire extinguished before B is ignited. Once B is linked, oxygen will be injected in A to enrich the air sufficiently to bring the burn down the drilled channel to the end of the casing by reverse combustion.

Forward burn will be started immediately, with oxygen in the lance and steam in the annulus between lance and casing. Flow rates will be controlled to maintain the burn zone at the injection point and to control channel growth and particulate emission.

The burn will be allowed to proceed at least until the cavity reaches the top of the coal seam. At this point we will evaluate the amount of coal consumed, the current gas composition, and the projected trend in heating value and decide whether to continue the experiment. It might be possible to achieve most of the goals of the experiment by stopping at this point.

After the main experiment is over, we anticipate that at least well C, and probably well B, will have survived. A forward burn could be carried out with injection in well B and production in well C. This would test the survival of a vertical injection well design and would enable us to study cavity

growth under different flow conditions. A few more HFEM wells could be drilled for cavity diagnostics or we could simply rely on injection well casing thermocouples and mass balance to provide the necessary data.

Assuming the injection well survives, the Uniwell or shaft gas concept could be tested in well C by adding an oxygen lance and reigniting at the base of the well.

The three experiments described can be carried out in sequence, either without interruption or with any time interval desired. Some interaction between experiments is inevitable but, with the well separations shown, we should be able to do at least two of the three with reasonable hope of success. Gas losses to the previous burn cavity are the most serious interaction anticipated.

There are two basic assumptions implicit in the design of this set of experiments. First, we assume that the cavity development and final burn geometry are not necessarily the same for air burns and for oxygen-steam burns. Therefore, we must test with oxygen if oxygen burn is the desired long-range goal. Also, we assume that we must continue the burn long enough to get interaction with the roof material and to at least begin a period of stable gas production. If a stable production period is not reached, it is impossible to be sure that all major problems have been observed and that the results truly represent those possible with that particular design.

The proposed experiment design is largely independent of seam thickness. Even for a thin seam it is a reasonable design for the first deep experiment. However, if successful, it could lead to commercial development of thick coal seams much more directly since this design is almost a module of a pilot plant.

In conclusion, we designed an experiment that has a high probability for producing a successful product with enough redundancy to allow for failure of any particular part. The possibility of completing as many as three separate experiments with one facility is included in the design.

A NEW METHOD FOR THE *IN SITU* GASIFICATION OF THICK COAL SEAMS—THE UNIWELL METHOD

Approximately 6% of the known U.S. coal reserves is in thick (greater than 50 ft), deep (greater than 500 ft) beds of coal.[5] This amounts to some 175 billion tons of coal. The majority of this coal cannot be mined economically because it is either too deep or too thick for conventional techniques. Current estimates indicate that if this coal were converted to synthetic natural gas at an overall efficiency of 50%, it would produce some 42 trillion m^3 of pipeline-quality gas—six times the proven U.S. natural gas reserve. In 1977 the U.S. consumed 620 billion m^3 of natural gas.

Environmental studies indicate that *in situ* coal gasification should damage the environment less than conventional methods of coal recovery. Most pollutants from the gasification process never reach the surface, and the gas-processing plant can be designed with pollution controls that trap waste gases such as hydrogen sulfide. Also, the hazards of mining are avoided, and no surface wastes are produced.

The common concept in all *in situ* coal gasification processes is to burn the coal underground under controlled conditions and use the heat evolved to generate combustible product gases. Air or oxygen pumped in through an injection well drilled from the surface maintains and controls the burning, and the product gases are conveyed to the surface through a production well drilled into the coal seam a short distance away. This concept presupposes a reasonably free passage for the injected air and the process gases. Solid coal, however, is seldom permeable enough to provide such a passage.

Horizontal connecting channels can be created in the coal seam by a variety of methods including reverse combustion and directional drilling. The success and reliability of this linking step determines the success of the subsequent forward gasification.

Figure 28 illustrates the procedure used to gasify thin and moderately thick seams of coal. The burn zone spreads outward and upward around the

5. Lawrence Livermore Laboratory, *An In-Depth Evaluation of LLL's R&D Program for the In-Situ Gasification of Deep Coal Seams*, Lawrence Livermore Laboratory, Livermore CA, TID-27008, February 1976.

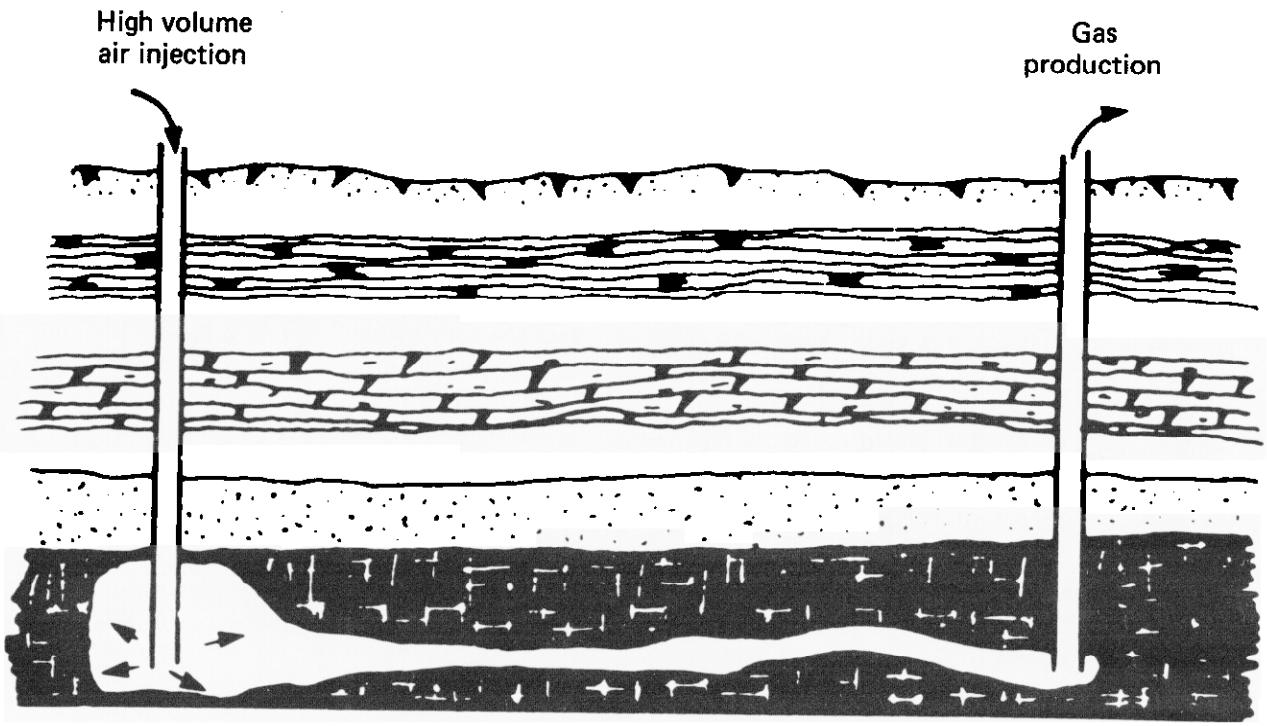

FIG. 28. The linking method, used to gasify thin and moderately thick coal seams.

injection well and soon reaches the top of the coal seam, as shown in the figure. From then on, the burn front moves horizontally, eventually consuming the coal between two wells. Heat escapes to the roof rock and some of the flow bypasses through cracks created as the roof collapses; thus, the heating value of the gas produced is less than that achieved during the early, pure-coal stage of the burn.

Large-scale gasification by this method involves linking and simultaneously gasifying an extensive well pattern, as shown in Fig. 29.[6]

The method is designed to burn out all coal in the area covered. For thin seams, the amount of sub-surface collapse is so small that no special precautions are needed to prevent the injection and production pipes from breaking. However, gasifying thick seams by this method may lead to serious problems of pipe survival because of the large shear forces caused by the more massive collapse.

The Uniwell Method

The uniwell method is designed to deal with the problems and opportunities offered by the very thick seams of low-rank shrinking coal available in the western United States. The major problem is the massive subsidence that will occur if a large area of thick coal is removed. The major opportunity is that the channels no longer need be horizontal in these very thick coal seams.

Figures 30 and 31 illustrate the basic concepts of the method. The oxidant (i.e., air, oxygen/steam, etc.) is injected and the produced gas is removed in concentric pipes in the same well. The flow channel for the produced gas is the uncased hole drilled through the coal seam. The injection piping passes through the center of this hole and ends near the floor of the seam. The method requires that the injection point be maintained at or near the bottom of the seam. This is similar to the "blind borehole method" developed by the British workers[7] except for the vertical configuration and emphasis on seam bottom injection

Injection near the bottom, with the subsequent deflection of the flow paths, creates a turbulent zone that promotes a radial extension of the burn zone. The coal is undercut so that as the coal above dries and shrinks, it will fall to the bottom around the injection pipe and create a large packed bed. The importance of bottom injection for controlling burn zone geometry was demonstrated during the LLL Hoe Creek No. 2 experiment[8]; when the injection point was changed from the top to the bottom of the seam channel, gas quality improved and the burn zone moved from the top to the bottom of the seam.

The continuously renewed packed bed of dried and broken coal should help ensure high gas quality. The hot process gas must pass through this bed, heating it further and driving off rich pyrolysis gases. The information available on gas quality from thick bed gasification in the ARCO experiment[9] indicates that the gas from pyrolysis is a substantial fraction of the total gas produced. Also the vertical geometry of the uniwell method will allow the pyrolysis products to escape up the production pipe without passing through the burn zone and being oxidized.

Free water in the coal seam that enters the uncased channel will be entrained in the product stream and removed from the well. This water will serve to cool the gas before it enters the well casing. If additional cooling is necessary to protect the pipes, water jets will be used to spray water into the gas stream. Since this water is used only for cooling, its quality is unimportant and it would most probably be recycled.

Oxygen/steam or oxygen/CO_2 injection can be used with this design very simply. Adding another concentric pipe around the injection pipe will provide an annulus for steam or CO_2 injection. This pipe also affords additional protection for the central injection pipe and may be used even with air injection so that more controlled cooling can be provided to ensure injection pipe survival.

Eventually the cavity will grow to the point that the roof will collapse. The symmetric location of the piping with respect to the collapse zone

6. Underground Coal Conversion DOE/ET-0100, June 1979.

7. "Recent Developments in Underground Gasification," C. A. Masterman, *Inst. of Min. Eng. Trans.*, London, August, 1958.

8. C. B. Thorsness, R. J. Cena, W. R. Aiman, R. W. Hill, and D. R. Stephens, *Hoe Creek No. 2: Underground Coal Gasification Experiment with Air and Oxygen/Steam Injection Periods*, Lawrence Livermore Laboratory, Livermore, CA, UCRL 80921, June 29, 1978.

9. J. H. Follick, D. Varisco, R. Schraufnagle and M. Day, "Results of Atlantic Richfield's Rocky Hill No. 1 Field Test," in *Proceedings of the 5th Underground Coal Conversion Symposium*, CONF NO: 790630, May 1979.

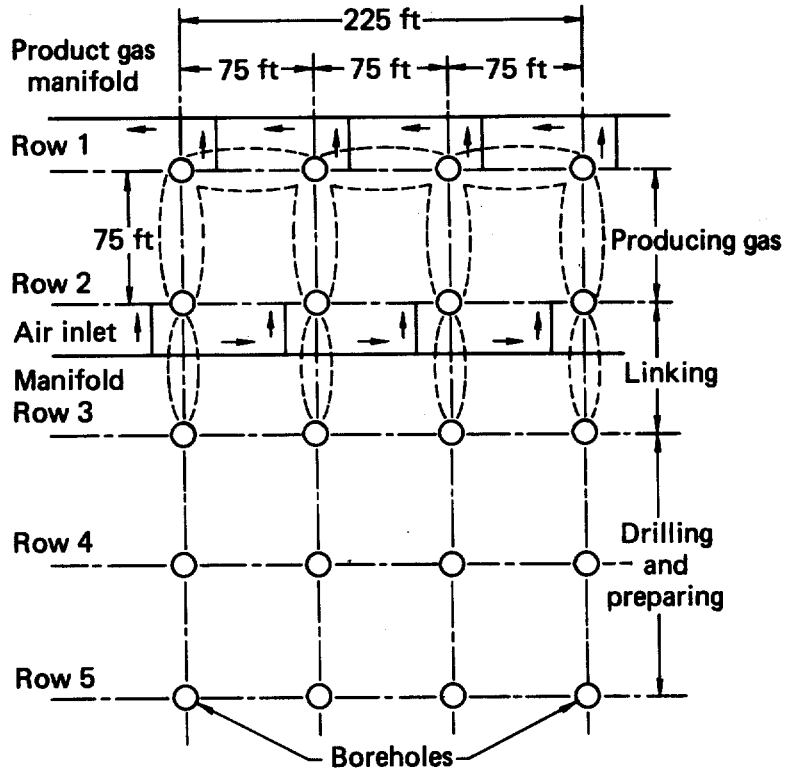

FIG. 29. Plan of a Moscow Region Plant, which has a shaftless generator. An extensive well pattern is simultaneously linked and gasified.

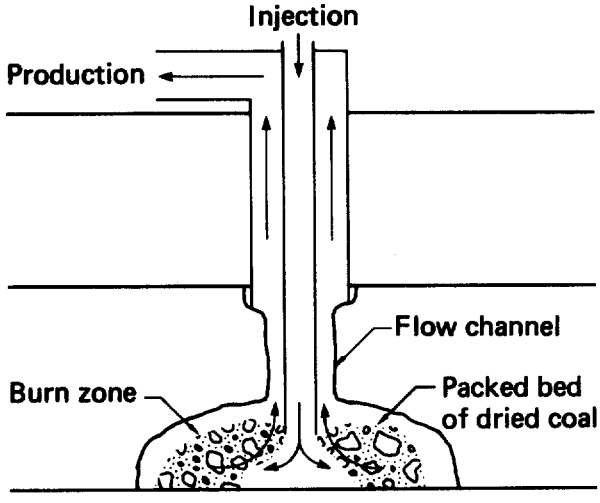

FIG. 30. The Uniwell method at an early stage of the burn.

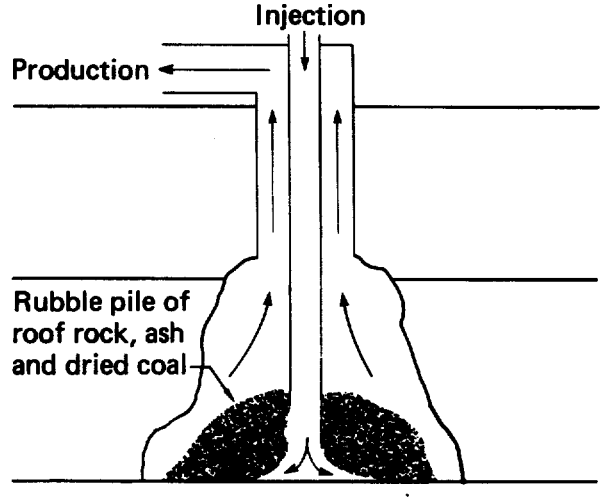

FIG. 31. The Uniwell method at a late stage of the burn.

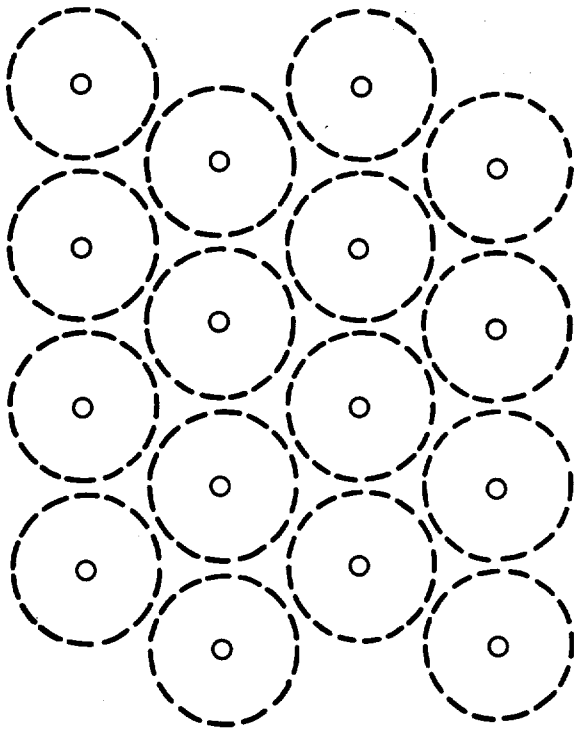

FIG. 32. Section of large-scale Uniwell system. Separating walls of unburned coal between wells are good isolaters (and thus minimize gas loss) and also prevent large-scale subsidence.

should reduce the shear forces to a manageable level and prolong the life of the well. Once the roof rock is exposed, gas quality will begin to decline, and at some point drop to a level that is unattractive for use. At this point, injection is stopped and the well is shut in.

Assuming a 50-ft-radius cylindrical burn in a seam 100 ft thick, 3.3×10^4 tons of coal would be consumed. If the thermal efficiency were only 50%, that amounts to 33×10^{11} Btu produced per well.

Assuming a well cost of $40 per foot in a seam 1000 ft deep, the well cost is $40,000 or $0.12 per million Btu.

The single well test is easily expanded to commercial size by combining the production from many non-intersection wells, as shown in Fig. 32. Retaining separating walls of unburned coal between wells will provide good isolation (less gas is lost) and also prevent large scale subsidence. Properly spaced wells should ensure that no surface subsidence occurs, thus minimizing the environmental impact of the coal use.

In summary, this method offers a number of advantages over other methods of *in situ* coal gasification.

1. Reduced drilling costs since the same well is used for both injection and production.
2. Eliminate the linking step since the link is automatically provided by the drilled hole.
3. Improved burn geometry by the continuous formation of a packed bed of coal around the injection point.
4. Reduced subsidence since the overburden is supported by walls of unburned coal between wells.
5. A long period of very high gas quality due to the pyrolysis products from the large packed bed formed.