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Effects of Stimulation Treatments on Coalbeds and Surrounding Strata

Evidence From Underground Observations

By William P. Diamond and David C. Oyler

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 9083

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

bbl	barrel	lbf/in^2(abs)	pound (force) per square inch, absolute
bbl/min	barrel per minute	lbf/in^2(ga)	pound (force) per square inch, gauge
ft	foot	lb/gal	pound (mass) per gallon
ft^3	cubic foot	Mft^3/d	thousand cubic feet per day
ft^3/d	cubic foot per day	min	minute
gal	gallon	MMft^3	million cubic feet
h	hour	pct	percent
in	inch	rpm	revolution per minute
lb	pound	std ft^3/min	standard cubic foot per minute
lbf/in^2	pound (force) per square inch	yr	year

EFFECTS OF STIMULATION TREATMENTS ON COALBEDS AND SURROUNDING STRATA

Evidence From Underground Observations

By William P. Diamond[1] and David C. Oyler[2]

ABSTRACT

Stimulated vertical boreholes are an effective means of removing gas from coalbeds in advance of mining. This Bureau of Mines report examines the coal mine roof damage potential of stimulation treatments. Twenty-two Government-sponsored stimulation treatments have been mined through to determine the effects on the coalbed and roof strata. Vertical fractures in the coalbed were discernible for most treatments and horizontal fractures were present for about half of the stimulations. Sand-propped vertical fractures were usually short in lateral extent. Evidence of stimulation fluid movement could generally be traced beyond the maximum extent of sand-filled fractures when fluorescent paint was added to the treatment fluids. The maximum lateral extent for a sand-filled vertical fracture was 416 ft and a paint-coated vertical fracture extended 630 ft. Horizontal fractures were generally found within bedding planes, most commonly on top of the coalbed. The maximum lateral extent for a horizontal fracture was 265 ft at a coalbed depth of 630 ft. Horizontal fractures have been found to occur as deep as 1,145 ft. Penetration of strata overlying coalbeds was observed in nearly half of the treatments intercepted. Most of these occurrences have been interpreted to be penetrations into preexisting joints. No roof falls or adverse mining conditions were encountered that could be attributed to the stimulations.

[1]Geologist.
[2]Mechanical engineer.
Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

The Bureau of Mines has developed several techniques, including the use of horizontal and vertical boreholes, to remove gas from coalbeds in advance of mining. Horizontal boreholes drilled from underground workings as part of the mining cycle have been shown to be very effective in providing short-term, immediate relief from high methane emissions (*1-6*).[3] This technique has been widely accepted in the coal mining industry, but it does require close coordination to integrate the drilling and subsequent gas drainage and disposal into the projected mine development plan.

Vertical boreholes can be placed several years in advance of mining to predrain gas from coalbeds over relatively large areas (*7-11*). The vertical borehole technique has the additional advantage over horizontal boreholes of allowing work to be performed on the surface instead of in the more restrictive underground environment. However, except for the relatively large-scale vertical borehole programs for both mine safety and for commercial production in the Black Warrior Basin of Alabama (*7, 9, 11*), the technique has been underutilized. The primary reason for this seems to be a combination of the economic conditions in the coal industry, legal questions as to the ownership of coalbed gas, and the potential of roof damage from the stimulation treatments. The question of potential roof damage is the subject of this report.

A total of 22 Government-sponsored stimulation treatments in coalbeds have been intercepted by mining. Twenty-one of these interceptions were in the eastern United States (10 in Pennsylvania, 7 in Alabama, 2 in West Virginia, and 1 each in Illinois and Virginia); only one in the western United States (Utah) was available for investigation. These underground interceptions have provided a unique opportunity to observe directly the actual effects of the stimulation treatments on coalbeds and surrounding strata. This report details observations previously presented in various forms by the Government and its contractors as well as information not heretofore reported, including the results of additional interceptions.

CONCEPTS AND LIMITATIONS OF UNDERGROUND OBSERVATIONS

Underground evaluation of areas surrounding boreholes that have been stimulated to increase gas production from coalbeds is an important step in obtaining information for the development of efficient stimulation treatments that do not adversely affect mining. By directly observing the effects of a particular stimulation design on a coalbed and surrounding strata and evaluating the observations in conjunction with thorough geologic characterization, valuable information can be obtained, especially early in the development stages of a methane drainage program. It is important to note that what is seen underground is dependent upon the area exposed by mining and the timing of observations in relation to the advance of entries. Obviously once a volume of coal is mined, anything contained in that coal is forever lost for direct examination.

Geologic characterization of available underground workings in the area to be drilled and stimulated is highly recommended before stimulation. This preliminary characterization aids in interpreting the underground observations and provides information for placement of the borehole and design of the treatment. These geologic studies should be continued as the entries are advanced toward the stimulated borehole and through the actual interception and advance beyond the borehole. The most complete characterization of this type was conducted in conjunction with Bureau of Mines contract J0333908, the final report (*12*) of which can serve as a model for future work.

The results of previously evaluated treatment mine-throughs indicate that it is quite likely that the predominant fracture wings will generally follow or penetrate the face cleat in the coalbed. The face cleat orientation can be determined by measuring cleat orientations underground if mine workings are available, or it might be inferred either from orientations in coalbeds exposed at the surface or from analysis of surface rock joints (*13-14*). The identification, characterization, and orientation measurement of roof joints is also important since it appears that many roof penetrations have actually been invasions into preexisting roof joints.

The cleat and roof joint orientation data can be used in placing the location of boreholes in relation to the mine development plan. This in turn can affect what is seen underground and possibly the seriousness of any penetration of existing roof joints. A borehole to be evaluated underground could be drilled so that it would be located in an entry to be intercepted by mining, allowing direct observation of the borehole, which would potentially provide the maximum information. Alternatively it could be placed in a pillar where less information may be gained, but where any roof penetration (which might or might not result in roof instability) near the wellbore would potentially not extend to the developed entries around the pillar.

If a borehole is to be mined through, it may also be possible to place it so that the probable face cleat orientation for an induced fracture would be parallel or perpendicular to the long axis of the entry (fig. 1). A hydraulically induced fracture in the face cleat direction and oriented parallel (or nearly parallel) to the long axis of the entry would be encountered "head-on" by the advancing entry (borehole 1, figure 1). This would provide an opportunity to perhaps observe the entire length of the fracture from its tip back to the borehole, if it was possible to observe the advancing face continuously during mining. However, once mining of the entry was completed, the fracture would have been consumed and would no longer be available for evaluation.

Butt cleat induced fractures, which are commonly shorter and less extensive than those in the face cleat orientation, would perhaps be observable on the ribs adjacent to the borehole. Complications could occur if roof joints (or other linear geologic discontinuities) are present in the entry and if they are parallel to the orientation of

[3]Italic numbers in parentheses refer to items in the list of references at the end of this report.

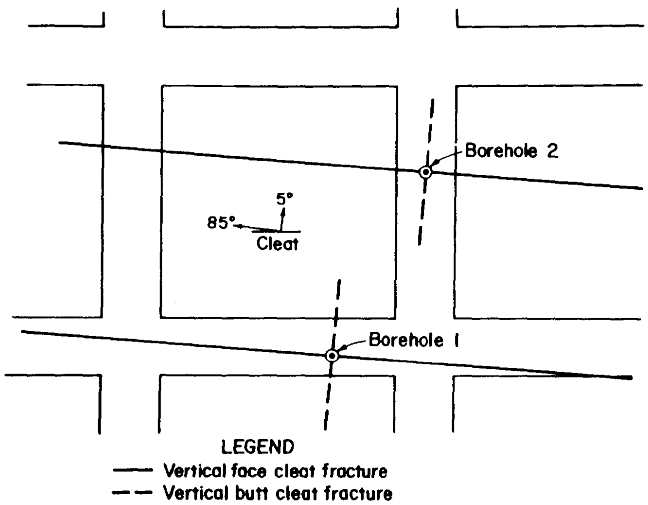

Figure 1.—Relationship of mine entry orientation and interception of vertical fracture wings parallel to coal cleat.

the face cleat, which commonly is the case. If the stimulation treatment penetrated into roof joints, resulting in roof instability, the hazard would potentially be exposed over a greater length in the entry if the joints paralleled the long axis of the entry than if the roof joint only extended across the width of the entry.

A hydraulic fracture trending in the face cleat direction perpendicular to the long axis of an entry would presumably be contained in the ribs adjacent to the borehole (borehole 2, figure 1) and would be available for observation as long as the pillar remained. Butt cleat fractures, if present, would have been intercepted head on. Since butt cleat fractures are often relatively short, they would often be completely mined by a single mining cut and never observed.

When the borehole is located in a pillar or other unmined area, there is always some uncertainty as to the exact location of the borehole. Knowledge of the exact location of the borehole is important in interpreting the underground observations, in terms of determining the length of the fracture wings and the presumed pathways (amount of stairstepping along face and butt cleats away from the borehole) of the treatment fluids through the coalbed. The uncertainty as to the borehole location results from the propensity for a borehole to deviate from vertical when drilled, and from inaccuracies in surveys of surface location, borehole deviation, and mine workings used to determine where the borehole should be underground.

Even with careful preplanning of the borehole location in relation to the expected underground location, it may not end up where it is expected. This was observed in the case of borehole SC-1 at the Soldier Canyon Mine in Utah. The bottom hole location of this borehole (as discussed in a later section of this report) was determined from a deviation survey to have migrated 35 ft laterally from the surface location. This should have placed it near the middle of an entry according to the mine plan. A thorough inspection of this area after mining failed to reveal any trace of the borehole or of the sand proppant and stimulation fluids, suggesting that one or more of the surveys must have been in error.

A significant aid in locating and describing the pathways of fracturing fluid movements underground is the use of fluorescent paint in the treatment fluids. By using a permissible ultraviolet light underground, the fluorescent paints can usually be readily identified and the extent of their pathways mapped. In general, when the fluorescent paint has been used, it has been possible to trace the movement of the fracturing fluids significantly beyond the extent of sand-propped fractures. Many different paint colors have been used, with the best results observed from orange, yellow, green, and red paint.

It should be noted that coalbeds sometimes contain naturally occurring fluorescent materials that may confuse the underground observations if paint similar in color to the materials are used. Red and pink fluorescing minerals were observed in the Upper Freeport Coalbed at the Lucerne No. 6 Mine in Pennsylvania, where red paint was used along with several other colors. Green fluorescing resins were observed in the Rock Canyon Coalbed at the Soldier Canyon Mine in Utah where green was used as the only paint color in the treatment. Blue fluorescent paint can be a particular problem, as was seen at the Lucerne No. 6 Mine, where hydraulic fluids used in the mining machinery also fluoresced blue making it difficult to differentiate the two.

During the stimulations at the Lucerne No. 6 Mine, different paint colors were injected at various stages of the treatment in an attempt to differentiate the effects of the different stages underground. The results of this experiment were somewhat varied because of the tendency for the last paint injected along a particular fracture to cover and mask any paint injected earlier.

Care must be taken in comparing underground observations of fluorescing paint tagged treatments to treatments where paint was not added. This is especially important in comparing maximum fracture length. In 5 of the 22 mined through treatments, fluorescent paints were used along with sand and in each case where any fractures were seen (four of five), it was possible to map the fluid movements beyond the presence of sand proppant. Paint was quite often observed on or in both vertical and horizontal fractures. Although it was obvious that treatment fluids had flowed through these fractures, it was not possible to determine if they previously existed or if they had been created by the treatment. Except in a few cases most fractures follow paths that look like cleat and bedding planes, and the fractures may have existed before the treatment began.

Experience with wells where fluorescing paint has been added suggests that, in shallow stimulated coalbeds, the major sand-filled fractures in the face and butt cleat directions are paralleled by networks of planes along which fluids, but not sand, have traveled. In addition, the fluids may also stairstep short distances along face and butt cleats to form a general fracture trend that does not parallel the face or butt cleat direction. Multiple horizontal planes of fluid movement have been identified with the use of fluorescent paint. As many as four horizontal planes have been observed in one case, although it is more common to see only one or perhaps two planes.

Vertical fractures may also lie over and connect to horizontal planes. These occurrences seem to be of limited extent, indicating that they may be fractures actually created by the stimulation process and therefore require too much creation energy to cover large areas when preexisting vertical and horizontal paths for fluid movement already exist.

BOREHOLE HISTORY AND RESULTS OF UNDERGROUND OBSERVATIONS

The available borehole completion and stimulation treatment data for each of the 22 mined-through stimulation treatments are presented in the following sections along with the results of the underground observations. Data are grouped together for each coalbed treated to aid the reader in locating and interpreting the results. Summary tables of the most pertinent data are included in the "Summary of Observations" section of this report. It should be noted that the coalbed mined and generally completed for gas production at the Oak Grove Mine is termed the Blue Creek Coalbed in this report, which is common usage in the mining district. Stratigraphically this coalbed is the bottom bench of the Mary Lee Coalbed (*15-17*).

BLUE CREEK COALBED, ALABAMA

OAK GROVE MINE, BOREHOLE TW-1 (*18-19*)

Borehole Completion

Borehole TW-1 was drilled 11 in. in diameter, using foam, to a depth of 1,115.25 ft and cased with 8⅝-in-OD casing to a depth slightly less than 1,115 ft. The bottom of casing was placed approximately 2 to 2.5 ft into the top of the target Blue Creek Coalbed, which was later reported to be 6 ft thick. The casing was cemented in place with an expanding type 16-lb/gal cement containing 18 pct NaCl. Approximate bottom hole pressure during cementing was 1,000 lbf/in^2(ga) ±100 lbf/in^2. After the casing was cemented in place, a 7⅞-in-diameter tricone roller bit was used to drill out the float shoe on the bottom of casing and to extend the hole to a depth of 1,133.25 ft, approximately 15 ft below the base of the Blue Creek Coalbed. An 8- to 10-lb/gal drilling mud was used for this short drilling interval, and the hole was circulated with clear water for several hours after the completion of drilling to clean the hole. At the time of completion, borehole TW-1 was approximately 520 ft ahead of mining.

Treatment Implementation (November 23, 1975)

The stimulation treatment record for borehole TW-1 is shown in figure 2. A discussion of the acquisition and limitations of stimulation treatment data is given in the appendix. The treatment utilized gelled water and sand proppant. The stimulation designed was generated with computer-based techniques that used formation parameters to estimate the character of the Blue Creek Coalbed. A treatment was selected that would theoretically produce two vertical fracture wings, each extending 423 ft into the coalbed with a sand proppant wing length of 143 ft.

The borehole was stimulated through 2⅞-in-diameter tubing set at 1,084 ft with a packer installed at the top of the wellhead to prevent the stimulation fluid from flowing to the surface in the annulus between the casing and tubing. No prestimulation cleanup or slotting of the coal face with a jetting tool was reported. The treatment was initiated with a 2,500-gal gelled water pad injected at rates averaging about 2 bbl/min. Surface treatment pressures quickly increased to about 1,400 lbf/in^2(ga), leveled off (indicating leakoff into the formation), then gradually increased to 1,775 lbf/in^2(ga) where formation break occurred with an accompanying sharp pressure decline to 600 lbf/in^2(ga).

After the formation break, the injection rate was increased to 10.5 bbl/min. The surface pressure increased to nearly 1,000 lbf/in^2(ga) and then gradually decreased to about 600 lbf/in^2(ga) throughout the remainder of the pad injection. An additional 2,500 gal of gelled water

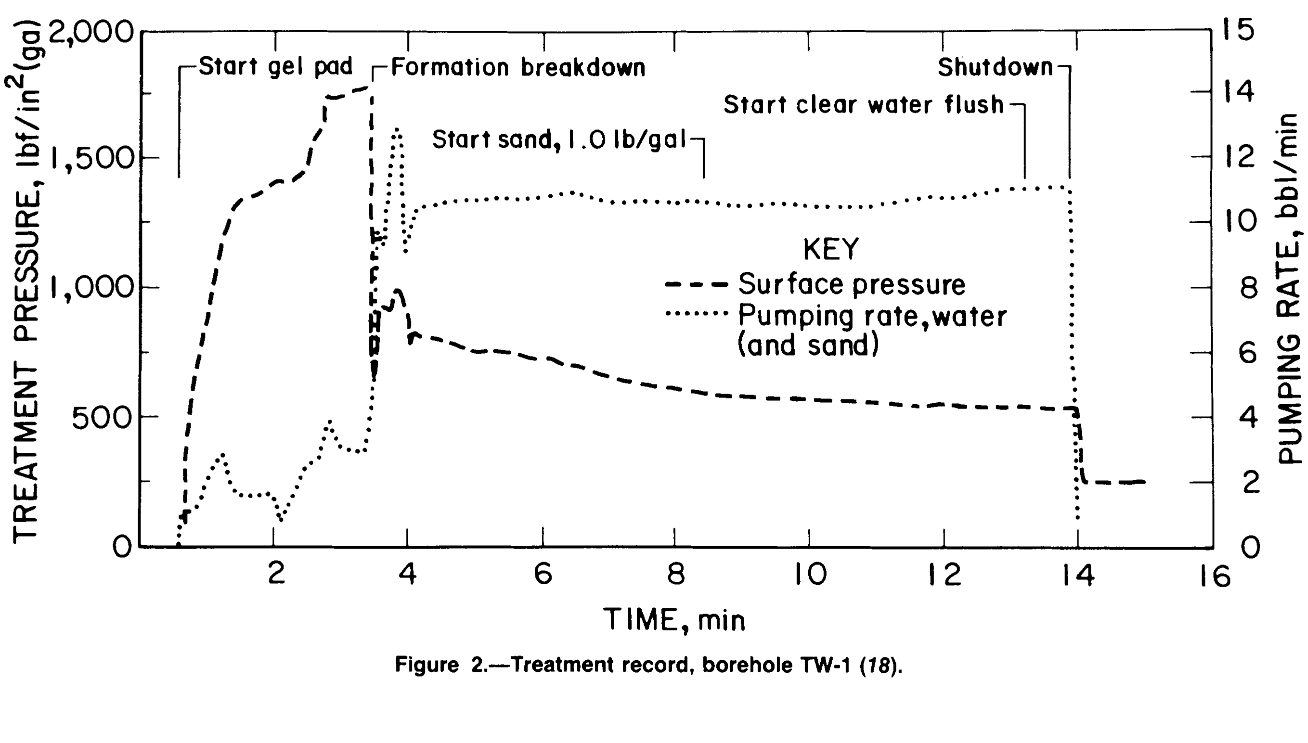

Figure 2.—Treatment record, borehole TW-1 (*18*).

containing 2,500 lb of minus 20- to plus 40- (20/40) mesh sand (at 1 lb/gal) was injected at a pump rate of 10.5 bbl/min. This was followed by a 290-gal fluid flush without sand. A total of 5,290 gal of fluid were injected during the treatment. Treatment pressures (surface) immediately after formation breakdown averaged about 650 lbf/in^2(ga). Surface treatment pressures averaged about 550 lbf/in^2(ga) during the sand injection stage of the treatment. An instantaneous shut-in pressure (ISIP) of 250 lbf/in^2(ga) (surface) was recorded at the end of the treatment. The ISIP is a measure of the minimum pressure required to keep a fracture open. Gas production from borehole TW-1 began at about 2,500 ft^3/d and gradually increased to a maximum of only 8,500 ft^3/d just prior to underground interception.

Underground Observations

Borehole TW-1 was mined through on June 20, 1976, approximately 7 months after stimulation. The area of the borehole interception is shown in map view on figure 3. Lambert (*18*) reports the presence of several vertical fractures that may have been propagated (or invaded) at slightly different times during the drilling and completion of the borehole. All fractures in coal were propagated within face cleats in a narrow zone (less than 1 in wide) with an average azimuth of N 65° E. Naturally occurring roof joints in the area had essentially the same orientations as the coal face cleat.

One fracture set extending in two wings from the borehole contained drilling mud and cuttings in a vertical face cleat plane. This fracture was apparently induced during the drilling of the short hole below the casing. The fracture extended from the base to the top of the coalbed and into the overlying roof shale. The fracture in the coalbed was ½ to ¼ in wide, with the widest part of the fracture occurring in the center of the coalbed where the coal was "softest." The thinner part of the fracture was near the roof and floor where the coal was "harder." The maximum lateral extent of this fracture was approximately 5 ft near the top of the coalbed to the northeast of the borehole (fig. 4). The lateral extent of the fracture diminished from the top of the coalbed to the bottom. The extent and geometry of this fracture to the southwest was not reported. Small patches of sand and gel were found in the fracture, indicating partial penetration by the stimulation treatment. The presence of "unbroken" gel in the fractures observed underground 7 months after the treatment is an indication that the viscosity reducing agent (breaker) did not perform as designed to reduce the gel viscosity within a few hours after the treatment was completed.

A second fracture (or upward extension of the mud-filled fracture) filled with the cement used to set the casing, was observed in the roof and a short distance into the top of the coalbed. The cement-filled fracture in the roof was traced 133 ft to the northeast and 48 ft to the southwest of the borehole and was generally ⅛ in wide. The fracture penetrated 13 in into the coalbed on the rib 24 ft northeast of the borehole and 7 in into the coalbed on the rib 48 ft southwest of the borehole. No penetration of the cement-filled roof fracture into the coalbed was reported at its maximum extent to the northeast. No evidence of horizontal fractures or adverse effects from the roof penetration by the vertical fractures was reported.

It was speculated by Lambert (*18*) that the bulk of the treatment was placed into the floor rock exposed in the wellbore below the coalbed. The primary evidence for this is the minimal amount of treatment fluids and sand observed in the exposed coal section around the borehole. Also, gas was bubbling up through the water filling the open wellbore in the mine floor. It was further speculated that the lower gas production rates observed from this borehole were the result of fractures being filled with drilling mud, cement, and unbroken gel, which prevented propagation of sand-filled fractures in the coalbed and also reduced fracture permeability near the wellbore, thus hindering gas and water flow.

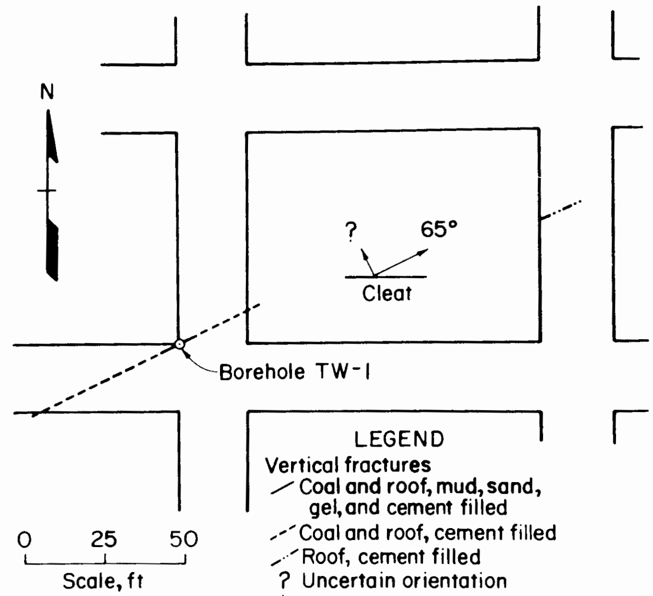

Figure 3.—Mine map, borehole TW-1, with fracture orientations (*18-19*).

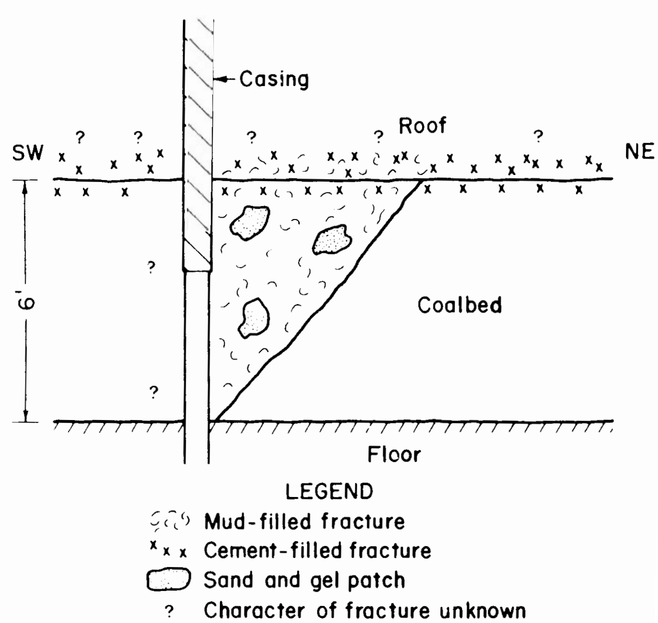

Figure 4.—Schematic cross section parallel to face cleat fractures at borehole TW-1 (*18*).

OAK GROVE MINE, BOREHOLE TW-2 (*20*)

Borehole Completion

Borehole TW-2 was drilled 6¼ in. in diameter to a depth of 857 ft, approximately 235 ft above the target Blue Creek Coalbed. The remainder of the hole, to the total depth of 1,150.6 ft, was drilled 6⅛ in. in diameter using an air-foam drilling fluid. The borehole was cased to its total depth with 4½-in-OD casing and the bottom 500 ft was cemented with 13.8-lb/gal cement. The top of the Blue Creek Coalbed was at a depth of 1,093.4 ft and the coalbed was 5.0 ft thick. At the time of completion, borehole TW-2 was located 600 ft in advance of mining.

Treatment Implementation (October 24, 1976)

Prestimulation strata characterization tests included natural gamma ray and gamma density wireline geophysical logs. Lambert (*20*) reported several interesting observations related to the use of the density logs, including the identification of the location of the slots cut into the casing and correlation of density changes in the coalbed to the type of fractures observed underground. These observations are summarized in the "Underground Observations" section of this discussion.

A jetting tool was used to cut slots through the casing at the target coalbed. The intent was to cut four vertical slots 90° apart, from the base of the coalbed to within 1 ft of the top. The tool was positioned using wireline geophysical logging tools.

The stimulation treatment record for borehole TW-2 is shown in figure 5. The treatment utilized gelled water as specified in table 1 and sand proppant. The stimulation

Table 1.—Specifications of gelled stimulation fluid, borehole TW-2 (*20*)

Base fluid		*Conc, per 10^3 gal H_2O*
Surfactant	gal	3
Fluid loss additive	lb	50
Gelling agent	lb	66.7
Breaker	lb	2
Complexer	gal	0.4

design selected would theoretically produce two vertical sand-filled fracture wings, 1 in wide and 5 ft high, each extending approximately 150 ft out from the borehole. The actual treatment was characterized by high injection pressures that averaged 2,400 lbf/in²(ga) at the surface. Maximum pressure recorded was 2,500 lbf/in²(ga). No obvious formation breakdown was observed by Lambert (*20*). An instantaneous shut-in pressure was recorded at 2,200 lbf/in²(ga) surface pressure. Fluid injection rates averaged approximately 8 bbl/min. Sand concentrations were generally 2 lb/gal, but were briefly increased to 4 lb/gal prior to completing injection of the planned sand weight. A total of 3,500 gal of gelled water and 4,000 lb of sand proppant (1,000 lb of 20/40-mesh, 3,000 lb of 10/20-mesh) were used in the treatment.

During uninterrupted water pumping periods, gas production averaged about 15,000 ft³/d with maximum temporary rates of 80,000 ft³/d immediately after servicing the downhole water pump. A complete history of the production rates and problems can be found in the paper by Lambert (*20*).

Underground Observations

Borehole TW-2 was mined through on February 15, 1977, approximately 4 months after stimulation. The area of the borehole intercept is shown in map view on figure 6. Figure 7 is a cross-section drawing of the face advanced approximately 4 ft beyond the borehole showing the induced fractures and the exposed well casing. Observations of the cased borehole revealed a poor cement job, with only about half of the annular space between the casing and the formation filled with cement in the roof and floor. Sand and/or gel filled the remaining portion of the annular space. No cement was found adhering to the casing within the coalbed interval. The only fully penetrating slots through the casing were found in the floor rock interval below the target coalbed. The casing had expanded outward in this interval where it was pierced by four roughly diamond-shaped slots nearly 5½ in long and 2 to 2½ in wide. The tops of the slots were

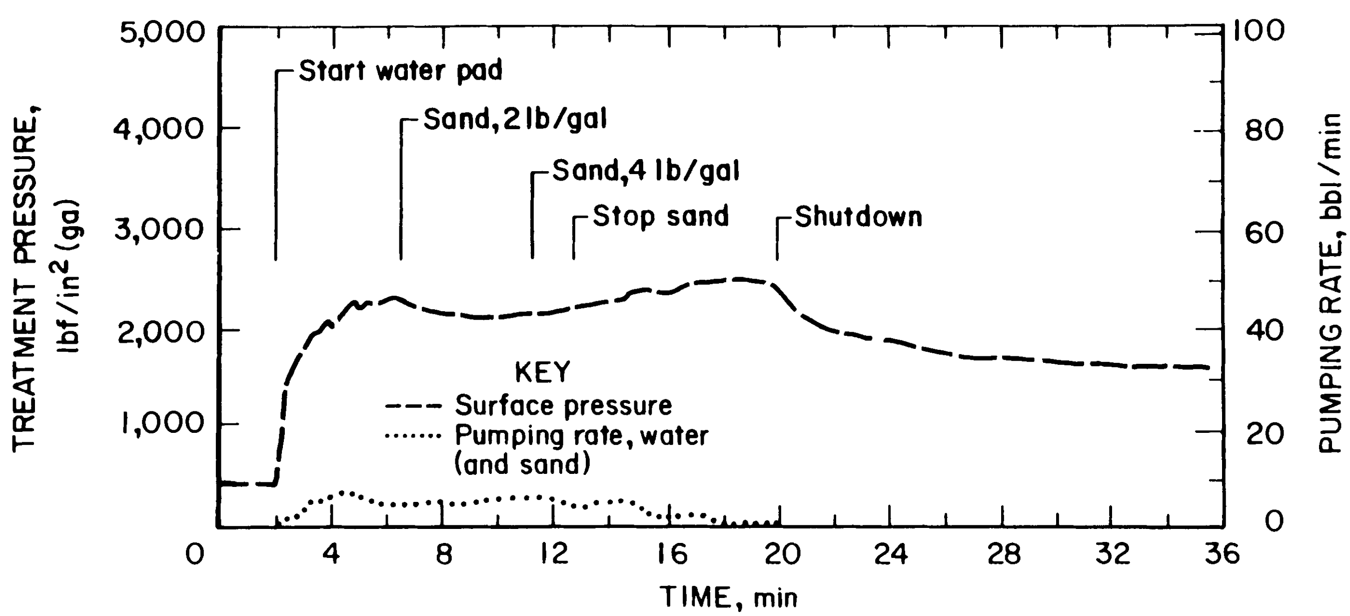

Figure 5.—Treatment record, borehole TW-2. (Modified from Lambert (*20*))

about 4 in below the base of the coalbed and were oriented N 60° E and N 15° W. In addition to the slots, five holes (0.3-in maximum diameter) were located in an interval 5 to 9 in above the slots.

Lambert (*20*) reported that before the start of production the presence of the slots only in the floor rock below the target coalbed could have been revealed by a comparison of density logs from before and after slotting operations (fig. 8). The logs run after the slotting show a significant density decrease along the casing interval identified by underground observation to have been successfully slotted.

Factors reported to have possibly contributed to the poor slotting included insufficient time allowed to cut through the casing; slight rotation or twisting of the tool as it was lowered through the prescribed interval; and the very soft, friable nature of the coal, which may have caused absorption of much of the cutting energy. Underground observations supporting these hypotheses include the presence of vertically oriented grooves on the inner surface of the casing opposite the coalbed interval where the casing had not been completely cut through, and location of the successfully cut slots and perforations adjacent only to the "hard" floor rock and "hard" lower portion of the coalbed.

The location of the slots in the hard floor rock below the target coalbed did not prevent the stimulation fluids from entering the coalbed, but may have contributed to the high initial treatment pressures. The high pressures throughout the treatment were attributed by Lambert (*20*) to the high viscosity of the treating fluid and to the flow resistance created by the small openings in the casing.

Three well-defined vertical sand-filled fractures were present in the hard lower coal interval shown in figure 7. The fracture on the right side of the face (location 1, figure 7) was 4½ in wide near the floor. To date this is the widest sand-filled coalbed fracture observed underground. The fracture narrowed significantly at the interface between the lower hard coal and the upper soft friable coal, inclined and eventually became horizontal near the top of the coalbed. The other two vertical fractures in the lower coal section (locations 2 and 3, figure 7) inclined and became horizontal at or near the hard-soft coal interface. Each of these fractures terminated at the base of the coalbed and did not penetrate the roof rock.

The vertical portions of the three sand-filled fractures were oriented as shown on figure 6, and, according to Lambert (*20*), "followed local fracture planes in the coal." The fractures to the north of the borehole (locations 2 and

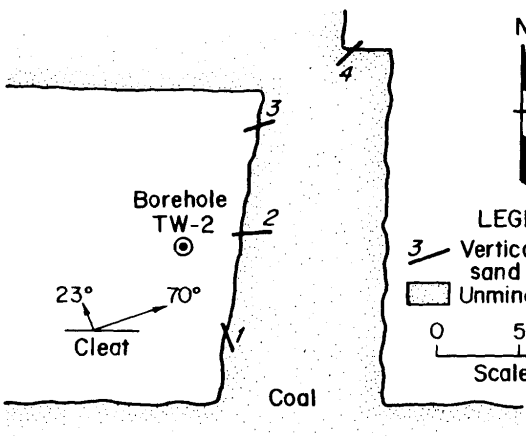

Figure 6.—Mine map, borehole TW-2, with fracture orientations. (Modified from Lambert (*20*))

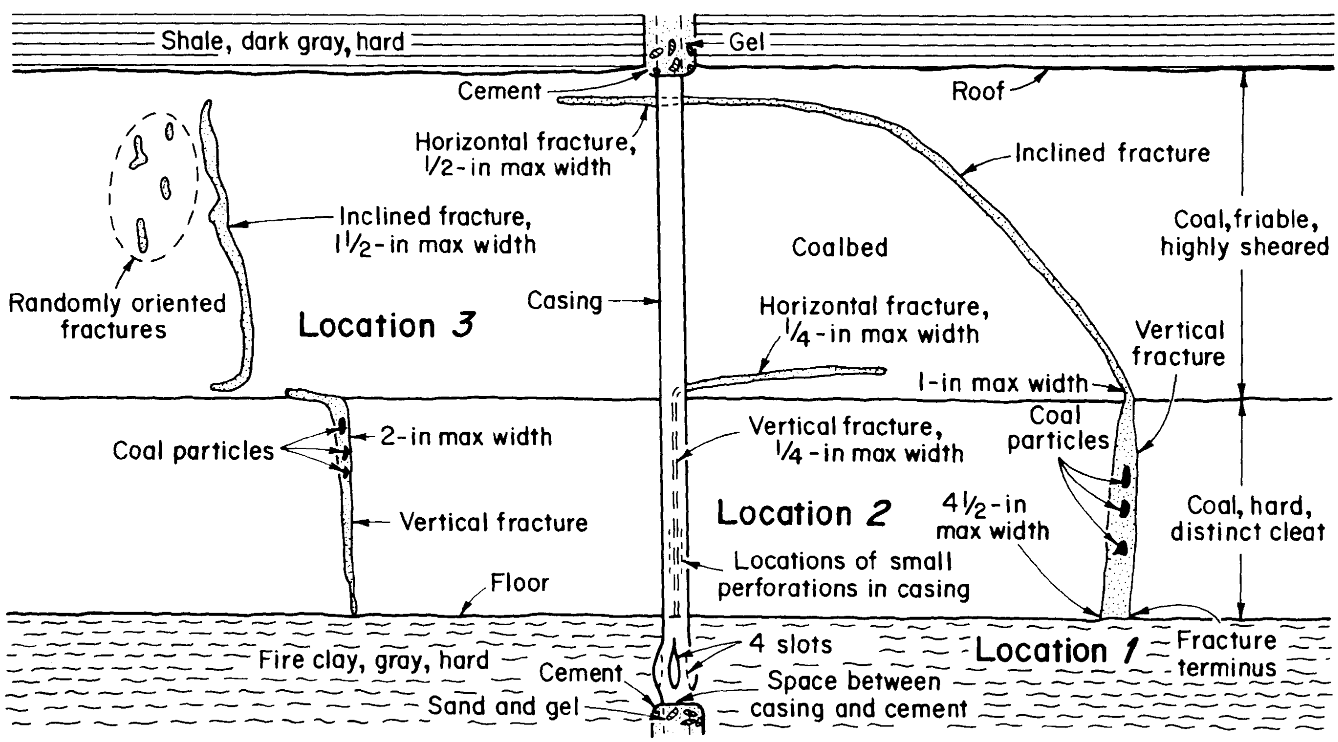

Figure 7.—Cross section of coal face at borehole TW-2, with fracture orientations. (Modified from Lambert (*20*))

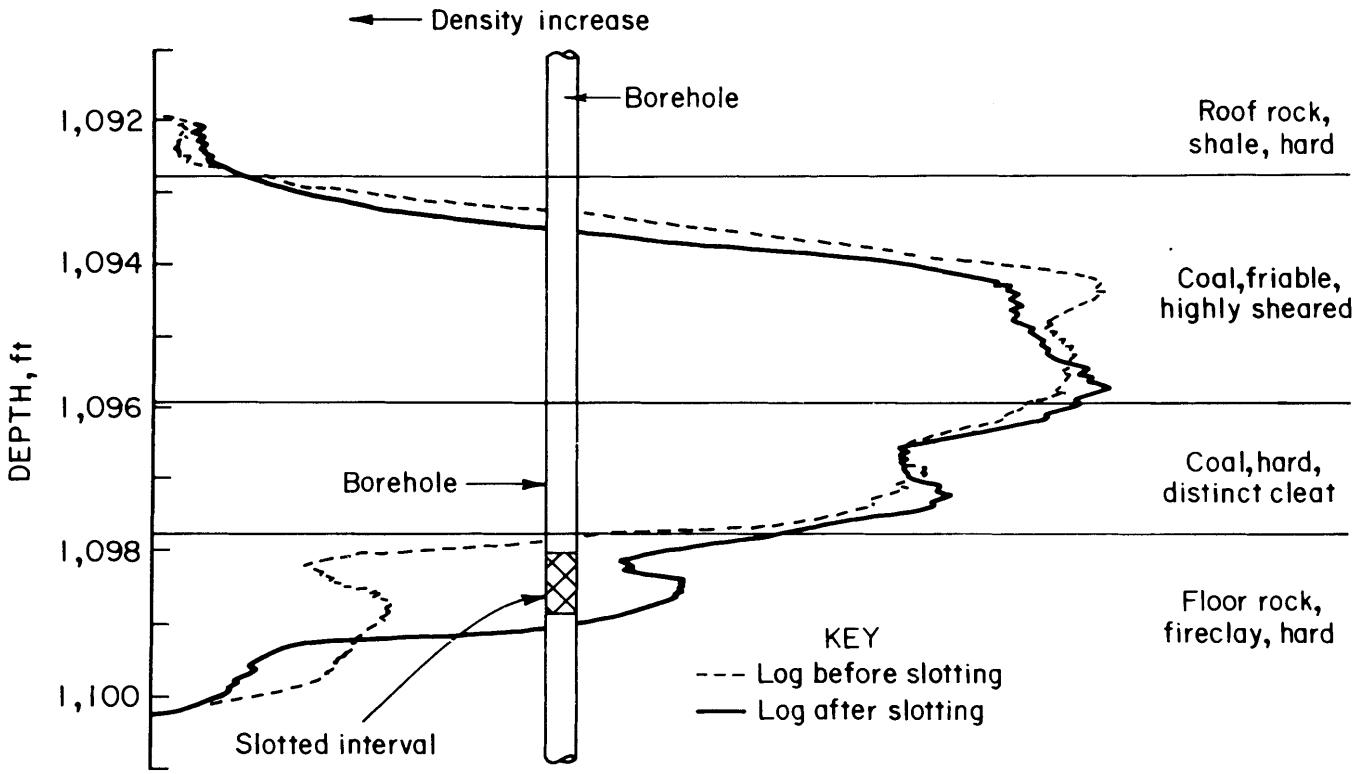

Figure 8.—Comparison of gamma density logs before and after jet slotting, borehole TW-2. (Modified from Lambert (*20*))

3, figure 6) were oriented generally in the face cleat direction (N 70° E), and those to the south (location 1, figure 6) appeared to be developed along butt cleats (N 23° W).

The two primary fractures observed in the more friable upper section of the coalbed appeared to have intercepted and propagated along inclined shear planes in the coal. No penetration of the roof strata was observed.

In addition to the common orthogonal vertical cleat system found in most coalbeds, the coal section at the Oak Grove Mine and other mines in the area displays secondary vertical and inclined fracture systems that intersect at various angles and with a variety of orientations (*16*). These complicated fracture systems are the result of the complex geological history of the area, and they can apparently influence the character of the induced fractures. Lambert (*20*) pointed out that the vertical fractures were contained in the lower, hard, distinctly cleated coal zone (correlated to the denser interval on the density log, figure 8) and that horizontal and inclined fractures were contained in the upper, friable, highly sheared portion of the coalbed (correlatable to less dense interval on the density log).

Examination of the entries developed around borehole TW-2 revealed only one other exposure of sand-filled vertical fractures (location 4, figure 6) to the northeast of the borehole. The maximum lateral extent of vertical sand-filled fractures was about 16 ft from the borehole. Horizontal sand-filled fractures extended a maximum of 8 ft from the borehole. It should be pointed out that the maximum 16 ft of observed lateral propagation of the vertical fractures is far short of the designed 150-ft sand-filled fracture length. The gelled fluids used in the treatment included an enzyme-type breaker to reduce the fluid viscosity within a few days, but the presence of unbroken gel around the casing as observed underground 4 months after the treatment, as previously described in the section on borehole TW-1, indicates that the breaker did not perform as intended. If unbroken gel was still present in the induced fractures, it is quite likely that permeability and gas production would be reduced.

OAK GROVE MINE, BOREHOLE TW-3 (*21*)

Borehole Completion

Borehole TW-3 was drilled 8 in. in diameter to a depth of 1,001.2 ft, approximately 73 ft above the top of the prime target of the Blue Creek Coalbed. The remainder of the hole was drilled 7⅞ in. in diameter, to the total depth of 1,113.5 ft, using foam as the drilling fluid. The borehole was drilled to a depth 30 ft below the base of the 5-ft-thick Blue Creek Coalbed. The borehole was cased with 4½-in-OD casing to a depth of 1,066 ft, approximately 2 ft into the 3-ft-thick Mary Lee Coalbed. Approximately 7 ft of rock separated the Mary Lee and Blue Creek Coalbeds.

The casing was cemented in place using a cement packer shoe, casing centralizers, and cement baskets in an effort to keep the cement from reaching the Blue Creek Coalbed in the open hole below the bottom of casing. The risk associated with this procedure was of cement leakage around the packer shoe and the potential of formation damage in the coalbed. A latex-based, low-fluid-loss class H cement with a 15.3-lb/gal weight was used in borehole TW-3. At the time of completion, the borehole was approximately 590 ft ahead of mining.

Treatment Implementation (November 21, 1976—Blue Creek, July 21, 1977—Mary Lee)

Prestimulation strata characterization tests included natural gamma ray, density, resistivity, self-potential, and neutron wireline geophysical logs. A jet slotting tool was used to cut three vertical slots, spaced 120° apart, into the Blue Creek Coalbed. This procedure was utilized to cut through any formation damage in an effort to ensure an open pathway into the coalbed prior to the stimulation treatment.

The Blue Creek Coalbed was stimulated with a 75-pct-quality nitrogen-generated foam and sand proppant. The stimulation treatment record for this borehole is shown in figure 9. An initial formation break was interpreted by Lambert (*21*) to have occurred at a surface pressure of 700 to 750 lbf/in^2(ga). After the initial formation break, fluid injection was briefly stopped to determine the instantaneous shut-in pressure, which was interpreted to be approximately 400 lbf/in^2(ga). Maximum and average surface treating pressures were approximately 1,500 and 1,400 lbf/in^2(ga), respectively, at injection rates averaging 10 bbl/min. The borehole was stimulated through $2\frac{3}{8}$-in-diameter tubing with a packer set in the casing near the bottom of the hole. A total of 20,000 gal of foam and 25,000 lb of sand (10,000 lb of 80/100-mesh and 15,000 lb of 20/40-mesh) were injected. The finer 80/100-mesh sand was used as a fluid loss additive to allow more of the stimulation fluids to propagate fractures instead of leaking away nonproductively into the formation.

Approximately 7 months after the stimulation of the Blue Creek Coalbed, the overlying Mary Lee Coalbed was stimulated. The Mary Lee Coalbed was characterized by Lambert (*21*) as being thin (3 ft thick) and containing several shale partings. The exact depth of the Mary Lee Coalbed in the borehole was determined through the use of wireline geophysical logs made prior to perforating the casing with shaped explosive charges.

The treatment was conducted through tubing using 5,040 gal of 75-pct-quality nitrogen-generated foam, 3,350 lb of 80/100-mesh sand, and 3,550 lb of 20/40-mesh size glass beads. The glass beads were used to aid in identifying any penetration of the stimulation treatment from the Mary Lee Coalbed into the Blue Creek Coalbed below.

A formation break was reported by Lambert (*21*) to be at a surface pressure of 600 lbf/in^2(ga). The maximum surface treatment pressure was reported to be 2,000 lbf/in^2(ga) with an average surface treatment pressure of 1,000 lbf/in^2(ga) at an average fluid injection rate of 5 bbl/min.

Gas production rates were generally erratic, especially early in the production history, but generally declined from a high of over 140,000 ft^3/d to 50,000 ft^3/d and then increased to 85,000 ft^3/d. After the stimulation of the Mary Lee Coalbed, gas production rose to a maximum of 45,000 ft^3/d. A complete production history of this borehole can be found in reference 21.

Underground Observations

A fracture from borehole TW-3 was intercepted in the Blue Creek Coalbed on October 6, 1977, approximately 10½ months after stimulation. The initial interception and underground observation of the fracture from borehole TW-3 did not include the mine-through of the borehole itself. Subsequently, entries were developed to the north of the borehole revealing the borehole and an extension of the earlier observed fractures (fig. 10). The fracture seen near the borehole was described by Lambert (*21*) as a single vertical sand-filled fracture, beginning as a hairline crack about 3 ft above the base of the coalbed, and gradually widening to approximately $\frac{3}{16}$ in at the top of the coalbed. The total observed lateral extent of this fracture to the southwest of the borehole was 80 ft.

The fracture continued upward at the same $\frac{3}{16}$-in thickness for an undetermined distance into the roof. The fractures observed within the coalbed contained mostly 80/100-mesh sand and the sand in the roof fracture was predominantly 20/40-mesh size. The glass beads used to stimulate the overlying Mary Lee Coalbed were not found in the Blue Creek Coalbed. Failure to contain the casing cement above the Blue Creek Coalbed was evidenced by the presence of cement in the same vertical fracture (coal and roof) as the sand proppant and as far as 80 ft from the borehole to the southwest. The orientation of the vertical sand-filled fractures in the coalbed and overlying strata

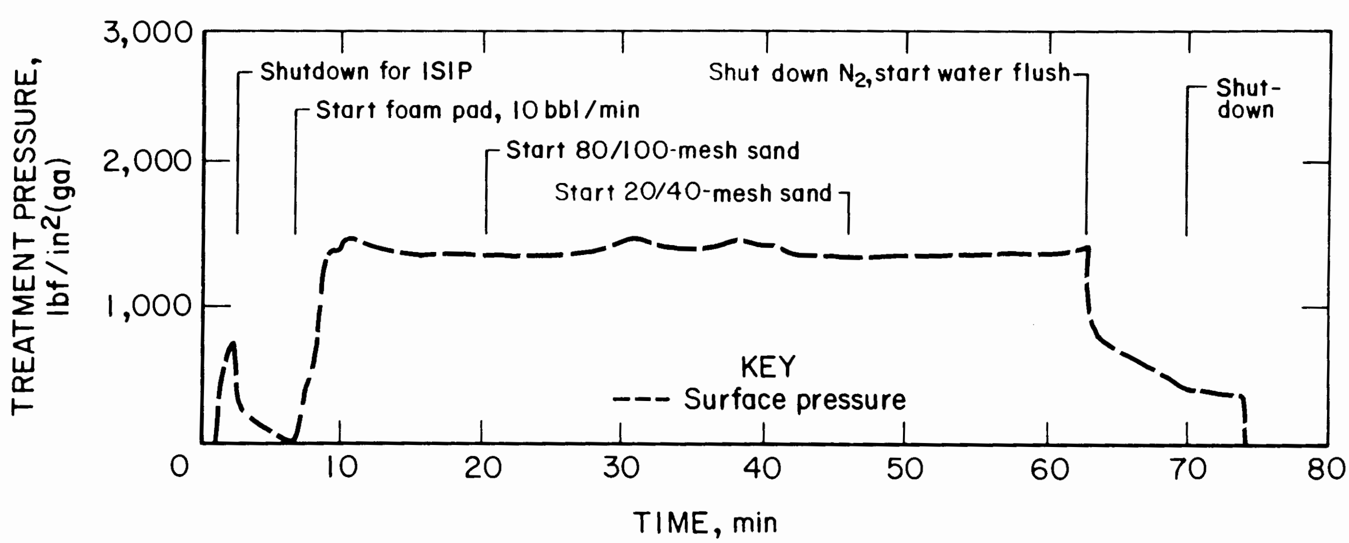

Figure 9.—Treatment record, borehole TW-3 (*18*).

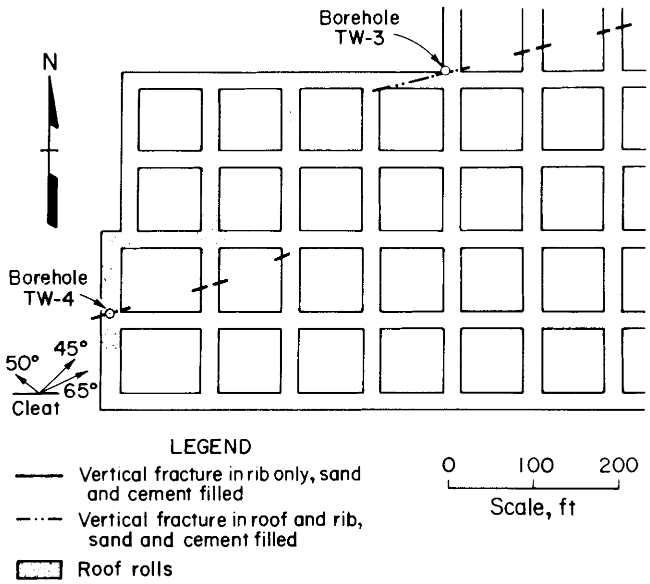

Figure 10.—Mine map, boreholes TW-3 and TW-4, with fracture orientations. (Modified from Lambert (*21*))

was N 67° E. Compilation of orientation measurements of naturally occurring roof joints (total of 57) in the vicinity of the borehole TW-3 (and the nearby borehole TW-4, to be discussed in the next section) indicated an average roof joint orientation of N 66° E. This orientation is essentially the same as that observed for the sand-filled roof fracture near borehole TW-3, and may be an indication that the sand-filled roof fracture was a preexisting roof joint entered by the stimulation treatment. The analysis of 357 cleat orientations in the same area produced a relatively broad range of readings (most face cleats were between N 45° E and N 65° E) with an average of N 53° E reported by Lambert (*21*). No horizontal fracture component was observed.

Borehole TW-3 was eventually mined through and a sand-filled vertical fracture trending N 68° E was traced across three new entries for a total lateral extent of 210 ft. Details of this fracture wing exposure are not available.

Supplementary roof support was installed in the vicinity of borehole TW-3. This is the only reported case out of 22 Government-sponsored stimulation treatments where supplementary support was deemed necessary by mine management. The evaluation of the situation and description of the additional support was described by mine management (*21*) as follows:

> The roof in the general area of TW-3 was of a quality typical of most of the mine developed to date; however, in the immediate area of the bottom of TW-3 in which both the upper and lower coal seams had been fractured, it was necessary to install supplementary roof support. This supplemental roof support was required when mine management observed roof movement along the west rib of the entry driven due north of the bottom of the borehole, additional draw rock separation, roof becoming excessively drummy, and water seeping out of cracks in the roof. The supplemental roof support consisted of boxing the intersection immediately to the south of the borehole with 6-inch H-beams, installing 4-inch H-beams supported by timbers for distances of 70 ft to the east and 40 ft to the north of the borehole, and installing 10-foot-long expansion-shell anchored roof bolts between the standard 4-foot-long resin roof bolts to ensure that the bolts anchored in the solid rock above the upper coal seam.
>
> Installation of the supplementary supports required additional time as well as close inspection by mine management to ensure its adequacy; however, it was possible to mine through this area without experiencing any roof fall during mining operations.

Lambert's (*21*) comments on the roof conditions in this area are as follows:

> The entry nearest TW-3 is also shown (fig. 10) to be a location of natural roof disturbances. Geologists also noted the presence of many wet roof joints in this area. Except for the single sand-filled crack leading from TW-3 (fig. 10), no evidence could be found to indicate that these wet roof joints had been created by stimulation. Unusually large amounts of seepage from roof openings near TW-3 could, however, be due to the borehole's presence, since it is an accumulation point for water within a coal unit only 7 ft above the open entry.

Lambert (*21*) further commented on possible reasons why the stimulation treatment for borehole TW-3 (and TW-4, to be discussed in the next section) did not remain in the coalbed:

> 1. The fine-mesh sand used as a fluid-loss agent was the only sand found to be contained in the coal. This sand is thought to have caused the propagating fracture to clog or screen-out in the coal early in the treatment. With continued pumping, it is possible that the fracturing fluids entered a preexisting plane of weakness in the shale roof rock. It is unlikely that this very hard roof rock was actually "broken" by the 1,400 psig pressure used during stimulation. No evidence could be found at either underground test site to indicate that the roof offered much resistance to the stimulation. Such evidence would include the presence of horizontal fractures or short propagations along butt cleat directions as was seen in other stimulation treatments.
>
> 2. Cement used to set casing in TW-3 (and TW-4) was found in the roof, and up to ±80 ft away from the wellbores. The roof strata was already broken or fractured sometime before casing was cemented in the test wells, probably just after the time when the holes were drilled.

OAK GROVE MINE, BOREHOLE TW-4 (*21*)

Borehole Completion

Borehole TW-4 was drilled 510 ft southwest of borehole TW-3 (fig. 10). It was drilled 8 in. in diameter to a depth of 995.5 ft, approximately 70 ft above the top of the target Blue Creek Coalbed. The remainder of the hole was drilled to a 7⅞-in diameter to the total depth of 1,086 ft, using clear water as the drilling fluid. The borehole was drilled to a depth 15 ft below the base of the 5-ft-thick Blue Creek Coalbed. The borehole was cased with 4½-in-OD casing to a depth of 1,065.7 ft, approximately 0.7 ft into the top of the Blue Creek Coalbed. The casing was cemented in place using a cement packer shoe and associated equipment and cement specifications as used on borehole TW-3. At the time of completion, the borehole was approximately 1,010 ft ahead of mining.

Treatment Implementation (July 18, 1977)

Prestimulation strata characterization tests included gamma ray, density, resistivity, and self-potential wireline geophysical logs. A jetting tool was used to cut two slots, spaced 180° apart, into the coalbed.

The Blue Creek Coalbed was to be stimulated through 2⅜-in-diameter tubing with a 75-pct-quality nitrogen-generated foam with sand proppant similar to that of borehole TW-3. However, the stimulation treatment had to be terminated prematurely when foam containing sand was observed flowing from around the outside of the casing at the wellhead, indicating a poor cement job. A total of 12,200 gal of foam with 12,520 lb of sand (10,000 lb of 80/100-mesh and 2,520 lb of 20/40-mesh) was used in the treatment. An initial formation break was interpreted by Lambert (*21*) to have occurred at a surface pressure of 700 to 750 lbf/in^2(ga), similar to that observed at borehole TW-3. The maximum surface treating pressure was 1,800 lbf/in^2(ga), with an average surface pressure of about 1,500 lbf/in^2(ga) for the treatment at injection rates averaging 10 bbl/min. The continuous stimulation treatment record for this borehole is shown in figure 11.

Borehole TW-4 was not equipped with a water pumping system, however, it still produced gas at rates as high as 183,000 ft^3/d. Rates averaged 150,000 ft^3/d then dropped sharply to the final measured rate of 40,000 ft^3/d prior to plugging. Lambert (*21*) reported that there was some indication when comparing the production histories of boreholes TW-3 and TW-4 that the two wells interfered with each other. It was also reported that there was evidence of nitrogen gas communication to TW-3 when TW-4 was stimulated, indicating the movement of fracture fluids to greater distances than could be traced by the presence of sand-filled fractures underground.

Underground Observations

Borehole TW-4 was mined through on November 16, 1977, approximately 4 months after stimulation. A single vertical sand-filled (mostly 80/100-mesh size) fracture, similar to those observed at the TW-3 borehole location, was found in the vicinity of borehole TW-4 (fig. 10). It began as a hairline crack about 3 ft above the base of the Blue Creek Coalbed, and gradually widened to approximately $^3/_{16}$ in at the top of the coalbed. The maximum lateral extent of this fracture to the northeast was about 220 ft on an average azimuth of N 67° E, similar to the orientation of naturally occurring roof joints in the area. Sand was again found in a roof fracture above the coalbed as at borehole TW-3. Mining did not proceed more than a few feet to the west of the borehole, therefore the maximum lateral extent in this direction is unknown.

A large quantity of casing cement was found below the packer shoe at borehole TW-4. Cement covered most of the exposed wellbore in the coalbed, except where the two slots, each 5 in wide, were cut 9 to 12 in into the coal. The orientation of these slots was found to be approximately 90° to the orientation of the sand-filled vertical fracture. Cement was also found in the sand-filled vertical fracture in the coal and roof.

An evaluation by mine management (*21*) of the roof conditions in the vicinity of borehole TW-4 is as follows:

> Because the roof of the mine in the general vicinity of TW-4 was of a quality which required installation of more roof support than used in many other portions of the mine, it was difficult to assess the effect of the fracture on the mine roof at this location. However, no further increment of supplemental roof support was required at the base of the borehole or along the fracture wings.

Lambert's (*21*) comments on the roof conditions in this area are as follows:

> Previous geologic inspection of the mine near TW-4 showed the well to be nearly surrounded by minor deformation and dislocations in the coal associated with lenticular shale ridges projecting from the roof. Areas of the mine where these features, called "rolls", were observed are shown in figure 10. Because inherent rock weaknesses develop near such features, these areas generally require some degree of additional roof support. The necessity for more roof support near TW-4 than used

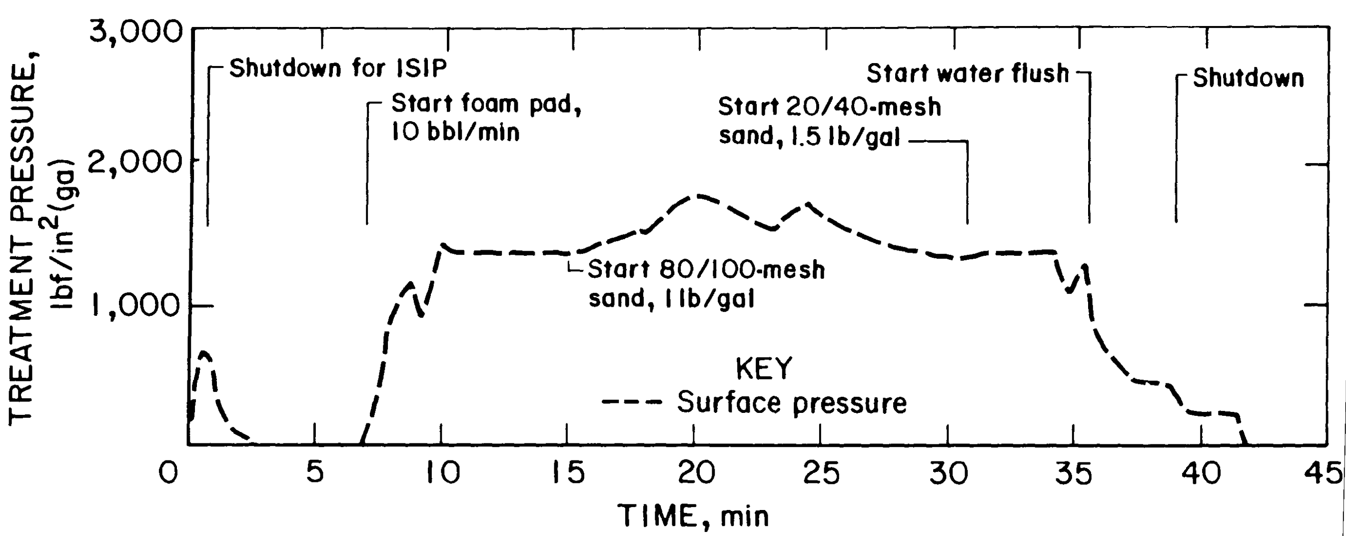

Figure 11.—Treatment record, borehole TW-4 (*18*).

in many other portions of the mine, as reported by mine management, may be attributed to this geologic phenomenon rather than stimulation of the test well. The fact that additional roof support was not required at the base of TW-4 nor was it required along the fracture wings indicates borehole stimulation was not the cause for providing additional roof support.

A discussion of the possible reasons why the stimulation treatment penetrated the roof is given in the previous section on borehole TW-3.

OAK GROVE MINE, BOREHOLE TW-5 (9, 22)

Borehole Completion

Borehole TW-5 was drilled 8 in. in diameter to a depth of 1,103.3 ft and 6⅝-in-OD casing was installed to a depth of 1,102 ft, approximately 43 ft above the top of the Blue Creek Coalbed at 1,145 ft. A 5⅞-in-diameter hole was then drilled out from the bottom of casing using air as the drilling fluid. This open hole section extended through the Mary Lee and Blue Creek Coalbeds to a total depth of 1,158.9 ft, approximately 8 ft below the base of the Blue Creek Coalbed. A stratigraphic section of the coal interval is shown in figure 12. The Mary Lee Coalbed is 2.5 ft thick and is separated from the 5.5-ft-thick Blue Creek Coalbed below by 6 ft of shale and thin coal stringers. The Blue Creek Coalbed was the target for gas production.

Treatment Implementation (December 16, 1978)

Prestimulation strata characterization included a suite of wireline geophysical logs (caliper, natural gamma ray, and density) and direct observation of the open hole

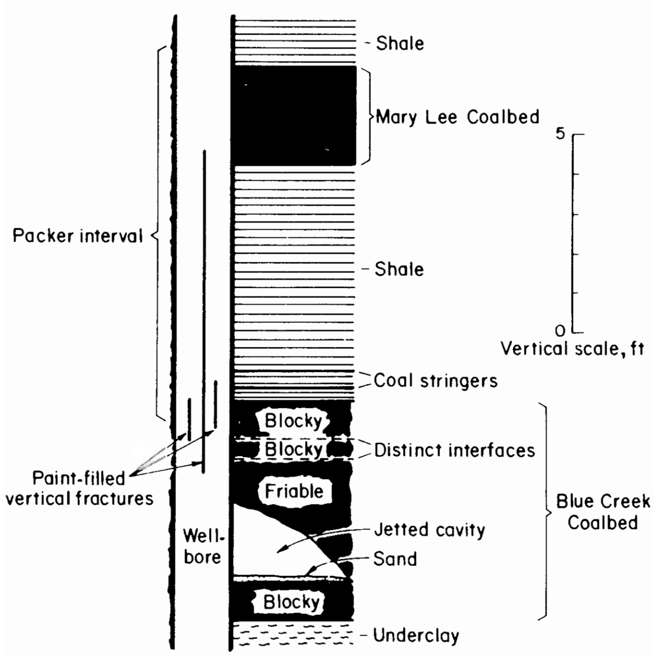

Figure 12.—Stratigraphic section and near-wellbore underground observations in the Mary Lee-Blue Creek Coalbed intervals, borehole TW-5. (Modified from Lambert (9) and Mahoney (22))

section with a submersible borehole TV camera. The TV camera was used to make a video recording of the borehole conditions for comparison with a planned poststimulation survey. The initial survey (*22*) indicated that the noncoal strata were "tight and unjointed" and the two coalbeds were "somewhat porous and cleated, although very little spalling had occurred during drilling."

Prior to stimulation, a horizontal slot was cut into the face of the Blue Creek Coalbed using a jetting tool. The two-port tool (180° apart) was positioned approximately at the midpoint of the coalbed and was continuously rotated at approximately 4 rpm for 27 min. A total of 2,268 gal of water and 5,500 lb of sand was used in the slotting process at a rate of 2 to 2.75 bbl/min. An average wellhead pressure of 1,800 lbf/in^2(ga) was observed during the slotting procedure. Coal returns were observed in the fluid returning to the surface. A downhole TV survey confirmed that a full 360° cavity had been eroded in the target coalbed.

To isolate the Blue Creek Coalbed from the rest of the open-hole section, an inflatable 10-ft-long packer was run on the bottom of the tubing. The rubber packer element was placed as shown in figure 12, and extended from 0.5 ft below the top of the Blue Creek Coalbed to a point 0.5 ft above the top of the Mary Lee Coalbed. Initial breakdown was achieved using clear water at a maximum pumping rate of 1.25 bbl/min. The breakdown pressure measured at the wellhead was approximately 1,000 lbf/in^2(ga). Before the primary foam treatment could be started, water was observed flowing at the wellhead from the annular space between the casing and the tubing. This observation was an indication that a fracture may have propagated through the strata around the packer, which would interfere with injection of an effective treatment into the Blue Creek Coalbed. The treatment was terminated at this point and the packer was removed from the hole. A slug (10 bbl) of fresh water containing 3 gal of red fluorescent paint and 1 lb of fluorescein dye, was injected into the formation for future underground characterization followed by an additional 10 bbl of water. A total of 2,200 gal of water was injected into the formation prior to abandonment of the initial treatment attempt.

Examination of the packer after removal revealed two 180° opposed, 1/16-in-wide impressions along a 6-ft length of the rubber element. These impressions were further characterized (*22*) by use of the TV camera as "score marks" in the wellbore "extending in a vertical direction from the top of the Blue Creek seam through the middleman to the base of Mary Lee seam." Mahoney (*22*) indicated that it was possible that the pressure used to inflate the packer element was sufficient to create the observed cracks before the actual injection of the water.

The packer was reinstalled at its previous position in the wellbore, and the Blue Creek Coalbed was successfully treated without any apparent leakage of treatment fluids around the packer. The treatment for borehole TW-5 was designed to utilize a 75-pct-quality nitrogen-generated foam without any sand proppant to investigate the production characteristics and the effect on the surrounding strata resulting from a no-proppant stimulation. The benefit expected from a no-proppant stimulation was confinement of the treatment to the coalbed (minimizing the potential for roof penetration and possible roof damage) by using low injection rates (*9*). Cost savings from deleting the sand proppant from the stimulation treatment were also anticipated, both from the reduced initial expenditures and also by decreasing the workover costs related to downhole pump failures experienced early in the production phase on previous boreholes using sand proppant.

Table 2 summarizes the treatment implemented in borehole TW-5. The continuous stimulation treatment record for this borehole is shown in figure 13. Foam injection began at a rate of 2 bbl/min and was increased in 1-bbl/min increments at 30-min intervals up to a rate of 5 bbl/min. The 5-bbl/min rate was maintained for 1.5 h and was then increased to 6 bbl/min for an additional 1.5 h. A total of 53,000 gal of 75-pct-quality nitrogen-generated foam was injected into the formation. Blue fluorescent paint and fluorescein dye were also injected with the foam to differentiate movement of the foam treatment fluid from the initial water injection when the treatment area was eventually intercepted by mining. The surface pressure gradually increased from about 1,500 lbf/in^2(ga) to a maximum of 2,000 lbf/in^2(ga) as the injection rate increased from 2 to 6 bbl/min. Average surface treatment pressures were about 1,900 lbf/in^2(ga).

A total of 6.6 MMft^3 of gas at an average rate of 49 Mft^3/d was produced during the 4.5-month production life of the borehole. A complete production history can be found in reference 22.

Underground Observations

Borehole TW-5 was mined through on July 12, 1979, approximately 7 months after stimulation. The borehole

Table 2.—Summary of treatment chronology, borehole TW-5 (22)

Time, min	Foam: Injection rate bbl/min	Foam: Volume, bbl	Wellhead pressure, lbf/in^2(ga)
0 to 30	2	60	0-1,550
30 to 60	3	90	1,600
60 to 90	4	120	1,700
90 to 180	5	450	1,750
180 to 270	6	540	1,750-2,000

was intercepted very close to the southeast corner of a pillar (fig. 14). A large cavity eroded by the jet slotting procedure was observed near the base of the borehole. The cavity appeared to be conical in shape with its base approximately 1 ft above the bottom of the Blue Creek Coalbed (fig. 12). Sand from the slotting procedures covered the bottom of the cavity. The height of the cavity was 23 in and the radius of the base was approximately 36 in.

Examination of the exposed wellbore revealed the two 180° opposed cracks first observed in the packer element and with the TV camera. The two primary fractures were developed in the upper part of the Blue Creek Coalbed and extended through the middleman into the base of the overlying Mary Lee Coalbed. Two additional short vertical fractures were also present near the top of the Blue Creek Coalbed (fig. 12). A paint-coated hairline vertical crack extended approximately 8 ft from the borehole and, according to Lambert (9), appeared to be a lateral extension of the vertical fracture observed at the wellbore. This crack was observed in the roof strata above the commonly mined interval. The commonly mined height includes the two coal stringers and intervening carbonaceous shale directly above the main bench of the Blue Creek Coalbed. The roof crack was oriented at N 66° E, close to the N 61° E predominant face cleat orientation.

The only other evidence of penetration of fracture fluids into strata above the mined interval was the presence of blue fluorescent paint in roof joints approximately parallel to the face cleat orientation at locations 25, 29, 30, and 31 at the distal end of the fluid penetration to the southwest (fig. 14). No adverse mining conditions or roof movement were reported associated with these roof penetrations.

Figure 14 shows the location and orientation of vertical paint-filled fractures observed in the vicinity of borehole TW-5. If an orientation on the fracture was not obtained but was recorded as being in the face cleat direction, the fracture trace was plotted as being oriented at an azimuth similar to that measured for nearby fractures. These fractures are identified by a ? in figure 14.

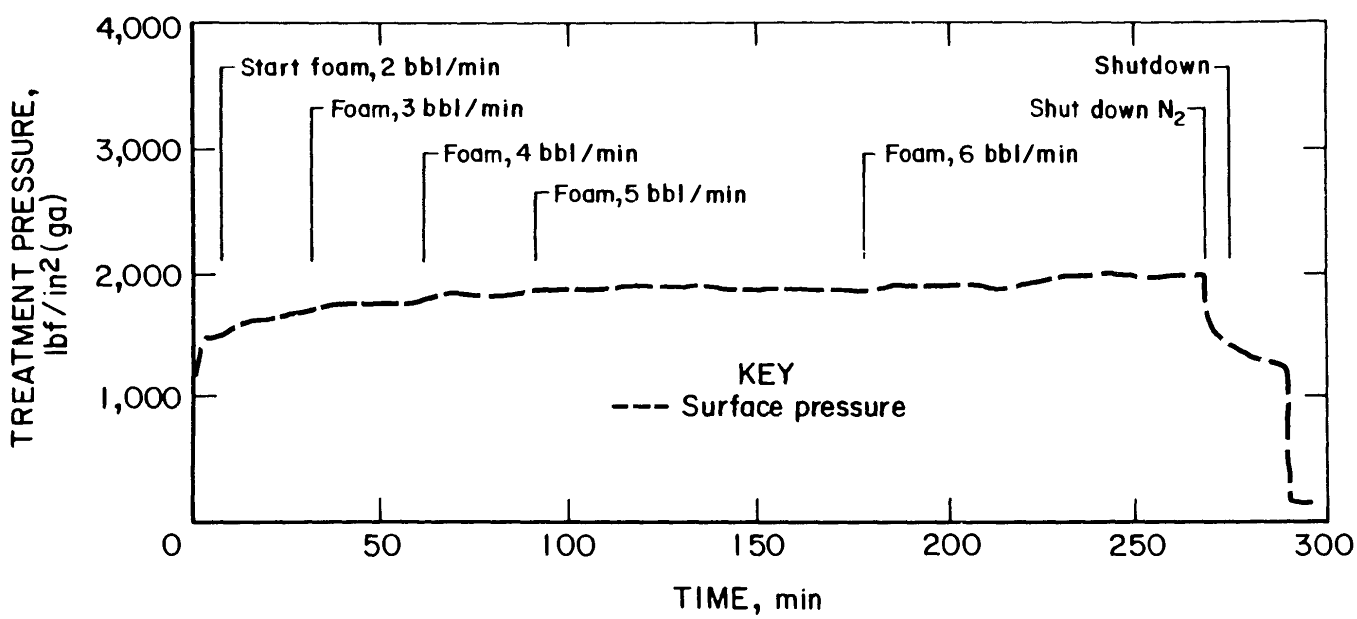

Figure 13.—Treatment record, borehole TW-5 (19).

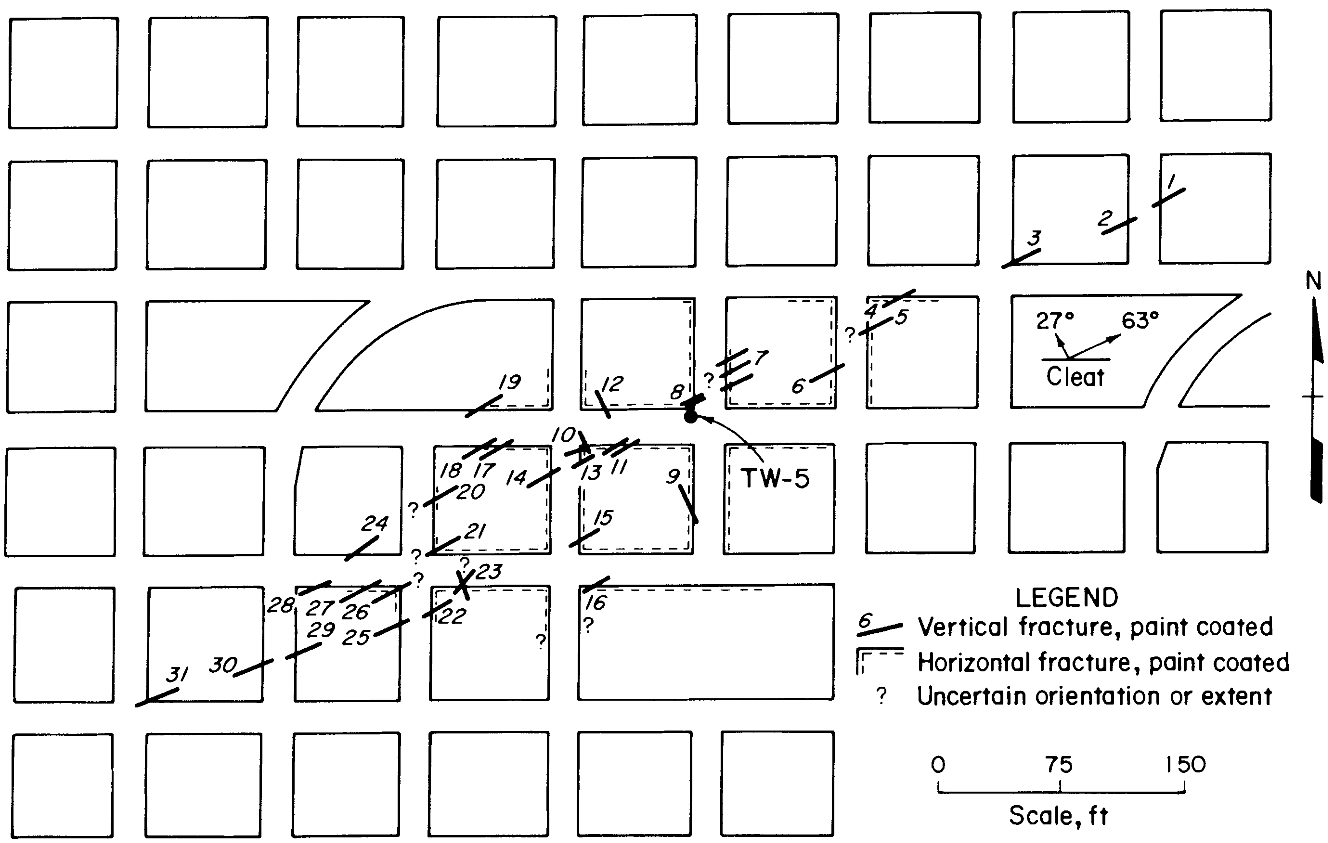

Figure 14.—Mine map, borehole TW-5, with fracture orientations. (Modified from Mahoney (*22*) and Boyer (*19*))

Table 3.—Summary of fracture observations (paint-coated surfaces), borehole TW-5 *(19)*

Location[1]	Fractures	Zone width, ft	Fracture description, vertical	Orientation	Paint color	Fracture description, horizontal
1	1	NAp	Top of BC to 1st coal stringer	N 60° E	NR	NR.
2	1	NAp	Top of BC to 2d coal stringer	N 63° E	NR	NR.
3	1	NAp	Top 3 in of BC to 2d coal stringer	N 62° E	NR	NR.
4	3	1	Top 1 in of BC to 2d coal stringer	N 61° E	NR	NR.
5	1	NAp	NR	NR	Blue	NR.
6	1	NAp	NR	N 61° E	Red	NR.
7	Zone	20	Small	NR	NR	NR.
8	Zone	5	NR	N 63° E, N 65° E	Red, blue	NR.
9	1	NAp	NR	N 29° W	NR	NR.
10	Zone	NR	Face cleat—top 15 in of BC to 1st coal stringer; butt cleat—generally top 8 to 15 in of BC; max top 30 in of BC.	N 69° E, N 26° W	NR	NR.
11	Zone	8	Floor to roof	N 54° E, N 59° E	1 red, rest NR.	On top of 1st coal stringer.
12	1	NAp	Top 18 in of BC to 1st coal stringer	Butt Cleat	NR	NR.
13	Zone	2	Floor to roof	N 60° E,	NR	On roof and on interface between blocky zones in BC.
14	Zone	5	Several floor-to-2d-coal stringers; rest NR.	N 59° E,	NR	On top of 1st coal stringer.
15	Zone	6	NR	N 58° E,	NR	NR.
16	1	NAp	Top 30 in of BC	N 60° E,	NR	NR.
17	1	NAp	Floor to 1st coal stringer	NR	Blue	On top of 1st coal stringer.
18	1	NAp	Top 12 in of BC to below 3d coal stringer.	N 59° E	..do	NR.
19	1	NAp	Top of BC to 1st coal stringer	N 59° E	..do	On top of 1st coal stringer.
20	Zone	NR	Floor to roof	Random	..do	NR.
21	1	NAp	..do	NR	..do	On top of 1st coal stringer.
22	2	NAp	..do	N 56° E	..do	NR.
23	2	NAp	Intersect at 60°	NE and NW	..do	NR.
24	1	NAp	Middle of BC to roof	N 50° E	..do	NR.
25	1	NAp	Floor to roof	NR	..do	NR.
26	1	NAp	Floor to 1st coal stringer	NR	..do	On top of 1st coal stringer.
27	1	NAp	..do	N 62° E	..do	Top of BC.
28	1	NAp	Middle of coal to top of coal	N 67° E	..do	NR.
29	1	NAp	Middle of coal to 2d coal stringer	N 56° E	..do	NR.
30	1	NAp	..do	N 56° E	..do	NR.
31	1	NAp	..do	N 62° E	..do	NR.

BC Blue Creek Coalbed. NAp Not applicable. NR Not reported. [1] Shown on figure 14.

Additional information on the actual observations for each numbered fracture or fracture zone is given in table 3.

The lateral extent of the horizontal paint-coated surfaces are also shown in figure 14. Horizontal paint-coated surfaces included the three highly polished slickensided surfaces at the top of the Blue Creek Coalbed and on top of the two thin coal stringers in the 1-ft interval directly above the Blue Creek Coalbed (fig. 12). One or more of the three horizontal surfaces were coated with fluorescent paint at any particular location, and without the presence of the paint, these interfaces penetrated by the stimulation fluids could not be differentiated from "normal" surfaces.

As discussed previously (*22*), general practice throughout the Oak Grove Mine is to mine up to the second coal stringer because the "slickensided coal surfaces demonstrated very little adhesion to the surrounding strata." Mahoney (*22*) also indicated that the inherent horizontal weakness at the top of the mined interval "appeared to have prevented upward growth of the induced fractures," and "it was not uncommon to observe an abrupt termination of the vertically decorated planes wherever they abutted one or the other coal stringer." The horizontal paint-coated surfaces as shown in figure 14 cover an essentially elliptical area with the long axis oriented approximately parallel to the face cleat orientation. The maximum extent of paint on a horizontal surface was approximately 230 ft to the southwest of the borehole.

Numerous vertical fractures or zones of paint-coated cleat surfaces were identified around borehole TW-5. Most of these fractures were oriented in the face cleat direction and only four locations (9-10, 12, 23) had butt cleats coated with paint (fig. 14). As with the horizontal fractures, the vertical fractures were only identifiable with the fluorescent paint and were essentially only the width of the face cleat itself. There appears to be a difference in the character of the paths of stimulation fluid movement observed to the northeast and to the southwest of the borehole. There are fewer vertical fractures or zones of fractures to the northeast than to the southwest (7 vs 24). The fractures to the northeast are generally confined to the upper portion of the Blue Creek Coalbed and the approximately 1 ft of overlying strata containing the two 1-in-thick coal stringers. Even the fractures close to the borehole at locations 7 and 8 are contained near the top of the coal interval. The fractures to the northeast are also contained in a narrow band very close to the axis of the elliptical pattern of the horizontal paint distribution.

The vertical fractures to the southwest (fig. 14), in addition to being more numerous, commonly extended the entire height of the coalbed (locations 11, 13-14, 17, 20-22, 25-27) as far as 220 ft from the borehole (location 27). At the remaining locations to the southwest, the vertical paint-coated fractures were confined to the upper portions of the coalbed up to the two overlying coal stringers. Zones of multiple paint-coated cleat surfaces appeared to be slightly more common to the southwest (locations 11, 13-14, 20, 23) than to the northeast (locations 3, 7-8). Single fractures predominated at locations farthest from the borehole. The vertical fractures to the southwest were found in a band with a maximum width of approximately 130 ft (from location 19 to 16) compared to the very narrow band of vertical fractures found to the northeast. The maximum lateral extent of vertical fractures was 370 ft at location 31 to the southwest.

The reason for the observed differences in the distribution of vertical paint-coated cleat surfaces may be related to a differential penetration capability along the face and/or butt cleat to the southwest and northeast. If penetration of cleat was easier to the southwest of the borehole, fluids would perhaps initially move along a face cleat in that direction until pressures built up sufficiently at the distal end to force the fracture along butt cleat. This stairstepping along face and butt cleats is a fairly common occurrence as noted throughout this report. Multiple repetitions of this stairstepping could produce the wider band of paint-coated fractures to the southwest of the borehole where the only butt cleat fractures were observed. The narrow band of fractures observed to the northeast of the borehole could have been induced at the same time as those to the southwest or near the end of the treatment when treatment pressures were not sufficiently high to continue fracture propagation to the southwest. There is also a wider dispersion of paint on horizontal surfaces to the southwest, perhaps indicating an easier horizontal penetration perpendicular to the long axis of the treatment fluid distribution in this area. The reason for the supposed easier penetration of cleat southwest of the borehole is unknown.

OAK GROVE MINE, BOREHOLE DHM-5 (*17*)

Borehole Completion

Borehole DHM-5 was drilled 6¼ in. in diameter to a depth of 1,376.5 ft, approximately 7 ft above the top of the target Blue Creek Coalbed at 1,383.5 ft, 4 ft into the parting between the Mary Lee and Blue Creek Coalbeds. The borehole was cased with 4½-in-OD casing to the total depth of the hole and the casing was cemented in place with API class A cement with 18 pct NaCl additive. The hole was completed 3⅞ in. in diameter to a total depth of 1,414 ft, approximately 25 ft below the bottom of the 5.6-ft-thick Blue Creek Coalbed.

Treatment Implementation (February 25, 1981)

A suite of strata characterization geophysical logs were run prior to stimulation. A jetting tool was positioned approximately 1.5 ft above the bottom of the Blue Creek Coalbed and rotated to create a horizontal slot in the coalbed exposed in the wellbore. Very little coal was seen in the fluid returns, therefore the tool was raised 3 ft after 15 min of jetting. A good coal return was observed at the new position. Water injection rates were 2.5 bbl/min with sand added at a rate of 0.8 lb/gal, for a total fluid volume of 145 bbl and 2,000 lb of sand. Surface pressures during jetting averaged 1,500 lbf/in^2(ga).

The stimulation treatment for borehole DHM-5 consisted of 75-pct-quality nitrogen foam without sand proppant and was conducted through tubing with a packer set in the casing. Formation break was reported by Boyer (*17*) at 800 lbf/in^2(ga) surface and 1,400 lbf/in^2(ga) bottom hole pressures. A continuous stimulation treatment record for this hole is not available. A 50,600-gal treatment was designed for this borehole, but only 40,866 gal of foam was used because of the excessive amount of water used in the jet slotting procedure and a problem with supplying water to the hilltop location. Pumping rates were 7 bbl/min throughout the treatment, with surface pressures ranging from 800 to 950 lbf/in^2(ga). Fluorescent paint was also added to the stimulation fluids at a rate of 1.5 gal per 5,000 gal to aid in underground delineation of the stimulation fluid movements. At the time of stimulation, borehole DHM-5 was approximately 2,900 ft ahead of mining.

Gas production from the no-proppant treatment in this borehole averaged 22,000 ft^3/d, which was more than the 2,000- to 3,800-ft^3/d rates Boyer (*17*) stated was typical of unstimulated wells in the area, but was about half of the average 50,000-ft^3/d rate for 17 stimulated wells at the mine site where sand proppant was used. Additional detailed production information can be obtained from reference 17.

Underground Observations

Mining approached to within 80 ft of the projected location of the borehole (fig. 15) but did not intercept the borehole. The exposure of the fracture on the face nearest the borehole was described by Boyer (*17*) as a vertical zone 4 to 5 in. in width in the upper third of the coalbed. The fracture was only identifiable by the presence of the fluorescent paint coating a series of parallel cleat with no apparent openings. This fracture was again observed entering the southern edge of the southeast corner of the pillar due east of the face location (fig. 15). At this point the fracture consisted of only a few paint-coated vertical cleat in a 1-in-wide zone confined to the upper 1 ft of the coalbed. This fracture continued through two adjacent pillars to the east for a total length of 340 ft. The orientation of the observed vertical paint-coated fracture was nearly east-west. No evidence of a horizontal fracture component was reported.

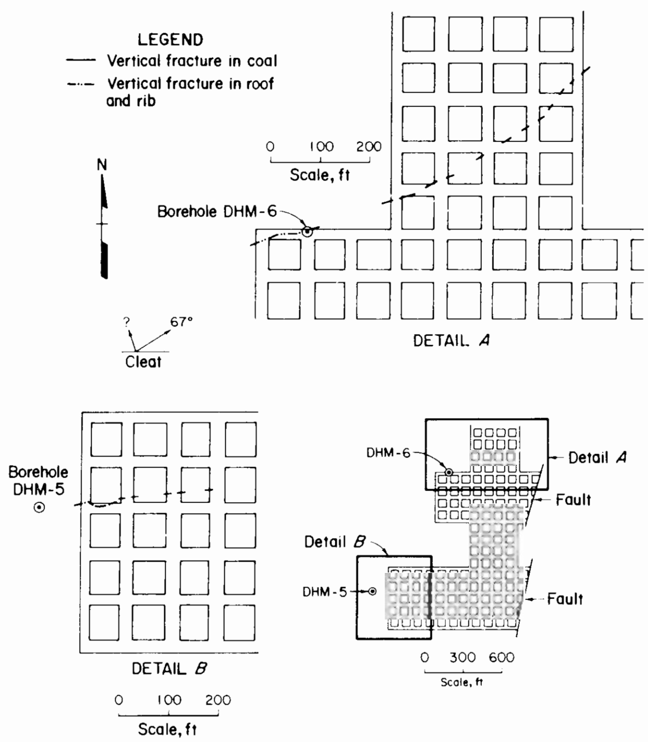

Figure 15.—Mine map, boreholes DHM-5 and DHM-6, with fracture orientations. (Modified from Boyer (*17*))

One paint-coated fracture in the roof strata above the coalbed was identified by the ultraviolet light to extend from the coal fracture observed nearest the borehole. Water was observed flowing slowly from the roof rock and coal in the vicinity of the fracture at this face. According to Boyer (*17*), the paint-coated roof penetration appeared to be following a preexisting joint in the roof rock.

Tracing the roof penetration away from the face across the entry revealed two locations where the east-west trending roof joint intercepted and stairstepped along north-south trending roof joints. The roof penetration extended laterally in an arc to the southern edge of the coal pillar to the east and appeared to be an extension of the coal fracture previously described in the upper 1 ft of coal at this point. No additional exposure of this roof penetration was evident, including the site of the additional coal fracture exposure on the eastern margin of the same pillar. Apparently the roof penetration terminated somewhere in the corner of the pillar. The last observation of the roof penetration was approximately 150 ft from the borehole. According to Boyer (*17*), the stimulation did not appear to affect mining operations, and no roof, floor, or coal stability problems were observed in this area of the mine.

OAK GROVE MINE, BOREHOLE DHM-6 (*17*)

Borehole Completion

Borehole DHM-6 was drilled 6½ in. in diameter to a depth of 1,246 ft. The hole was to have been drilled to a point into the shale parting between the Mary Lee and Blue Creek Coalbeds so that the Blue Creek Coalbed could be completed open hole. However, the driller did not recognize drilling into the Mary Lee Coalbed and he continued drilling, eventually drilling through the Blue Creek Coalbed and approximately another 1.6 ft below before drilling was stopped. The hole was cased to the total depth with 4½-in-OD casing, which was cemented in place with API class A cement with 18 pct NaCl additive. An additional 40 ft of 3⅞-in-diameter hole was drilled below the casing before wireline geophysical logs were run to evaluate the hole and locate the target Blue Creek Coalbed. The Blue Creek Coalbed was identified at 1,238.6 to 1,244.4 ft for a total of 5.8 ft of coal, all inadvertently behind casing. The parting between the Mary Lee and Blue Creek Coalbeds was 10.8 ft and the Mary Lee Coalbed was only 1 ft thick at this location.

Treatment Implementation (December 20, 1980)

A jetting tool was positioned at 1,244 ft, near the bottom of the Blue Creek Coalbed interval to cut two vertical slots through the casing and cement to expose the coalbed to the wellbore. A good return of coal was obtained in the water circulated to surface during the jetting, indicating a successful penetration into the coalbed. Pressures recorded at the surface during the slotting varied between 1,800 to 2,000 lbf/in^2(ga). The water injection rate was 3 bbl/min with a sand rate of 2 lb/gal for a total fluid volume of 80 bbl of water containing 1,500 lb of sand.

The stimulation treatment began with a 75-pct-quality nitrogen-generated foam pad at an injection rate of 3 bbl/min and was increased in 1-bbl/min increments until a rate of 7 bbl/min was reached (table 4). A surface breakdown pressure of 700 lbf/in²(ga) was reported (*17*). A total of 40,320 gal of foam pad was injected into the coalbed before the addition of 20/40-mesh sand proppant. Sand was added to the treatment at a rate of 1 lb/gal of foam while the foam rate stayed constant at 7 bbl/min. A total of 10,000 lb of sand was injected with 10,248 gal of foam during the final 35 min of pumping. Fluorescent paint was included with the treatment fluids. Surface pressures ranged from 800 to 900 lbf/in²(ga) during the treatment.

Bottom hole pressures were continuously monitored during the stimulation treatment and are presented in figure 16. The bottom hole pressure increased steadily as the injection rate was increased, up to a rate of 4 bbl/min. At the 4-bbl/min rate the bottom hole pressure began to decline, even though the injection rate was progressively increased to 7 bbl/min. The bottom hole pressure increased only slightly when sand was first added to the treatment, but as sand injection continued, the pressure gradually dropped. The bottom hole pressure never returned to the maximum observed at the 4-bbl/min injection rate.

Table 4.—Summary of treatment chronology, borehole DHM-6 (*17*)

Time, min	Foam: Injection rate, bbl/min	Foam: Volume, gal	Av bottom hole pressure, lbf/in²(ga)
0 to 15	3	1,890	1,050
15 to 30	4	2,520	1,100
30 to 60	5	6,300	1,090
60 to 90	6	7,560	1,080
90 to 165	7	22,050	1,090
165 to 200	[1]7	10,248	1,080

[1]With sand added.

At the time of the stimulation, the borehole was located approximately 1,800 ft from active mining. Gas production from this borehole quickly reached 80,000 to 90,000 ft³/d and remained at this rate until March 16, 1981 (approximately 3 months after stimulation) when the east wing of the fracture was intercepted by mining at a location 160 ft northeast of the borehole (fig. 15). Production rates declined and were somewhat erratic after the mine-through of the east fracture wing, but generally ranged between 40,000 to 50,000 ft³/d until mining came very close and finally intercepted the borehole in early 1982. A more complete production history can be found in reference 17.

Underground Observations

Inspection of the well casing exposed by mining of the Blue Creek Coalbed revealed two vertical slots, 180° apart, cut in a northeast-southwest direction. A vertical fracture zone, 1 to 2 in. in width and confined to the upper 3 ft of the coalbed, was observed on the rib 2 ft to the northeast of the borehole. The fracture zone consisted of multiple vertical planes, a maximum of 1/16 in wide, propped with sand and coated with fluorescent paint. A single vertical sand-and-paint-coated fracture was also observed in the 2 ft of exposed roof rock at this location. Boyer (*17*) commented that it was "difficult to ascertain if the roof fracture was produced by the hydraulic stimulation or if the hydraulic stimulation opened a pre-existing roof joint." The northeast wing of the fracture was next observed on the rib around the corner from the previous exposure, and 180 ft from the borehole (fig. 15). The fracture was still confined to the upper 3 ft of the coalbed, but consisted of a 10- to 12-in-wide zone of multiple vertical paint-coated face cleat surfaces with no sand proppant. The fracture terminated at the characteristically smooth, mirrorlike slickensided surface at the top of the coalbed. No penetration of the roof was observed at this

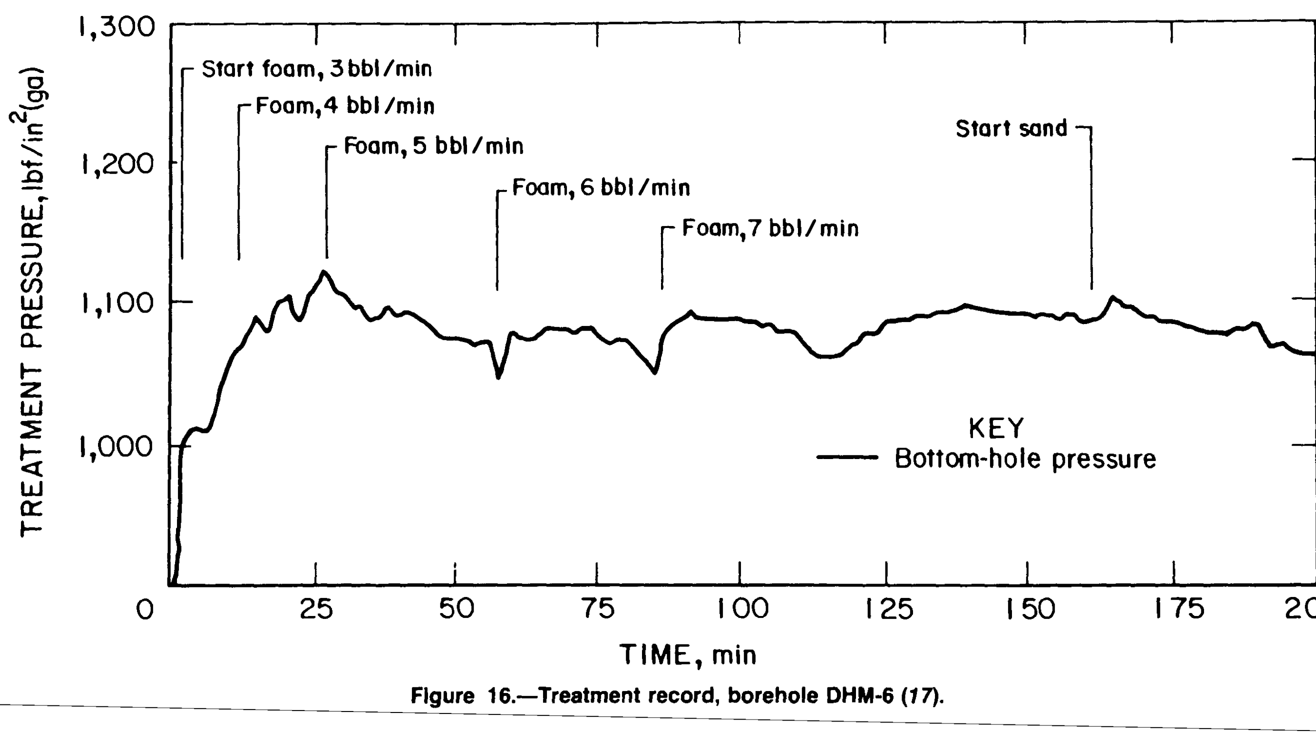

Figure 16.—Treatment record, borehole DHM-6 (*17*).

location or any further along this fracture wing. The fracture could be traced an additional 450 ft across the five entries to the northeast, finally entering the barrier pillar 630 ft from the borehole, the longest vertical fracture traced underground to date. The fracture was generally uniform in character across the five entries, consisting of multiple paint-coated vertical cleat surfaces in a narrow zone at the top of the coalbed. At the last observation point the fracture consisted of a 1- to 2-in-wide zone in the upper 1 ft of the coalbed. The northeast fracture wing varied slightly in orientation through its 630-ft traceable length, but generally followed an orientation of N 67° E, essentially the same orientation measured for face cleat at the mine site. No horizontal component was observed at any location along or in the vicinity of this fracture wing.

The vertical fracture wing to the southwest was observed on the rib 95 ft from the borehole (fig. 15). The fracture consisted of multiple vertical planes propped with sand and contained fluorescent paint in a 1- to 2-in-wide zone confined generally in the upper 3 ft of the coalbed. Small amounts of sand and paint were also seen in the lower portion of the coalbed. The fractures were oriented similarly to those in the northeast wing and appeared to be face cleats. No horizontal component was observed at this location. A single sand-and-paint-coated fracture, ¼ in wide, was present in the mine roof at the wellbore and was traced to the mine face 95 ft away. Small amounts of gas and water were flowing from the roof fracture near the wellbore, and from the fracture at the coal face. Boyer (*17*) concluded after detailed observations of the mine roof that this roof fracture was probably a preexisting roof joint that had been penetrated by the stimulation fluid and proppant. He also stated that "no roof or coal stability problems were experienced in this area of the mine."

PITTSBURGH COALBED, PENNSYLVANIA

VESTA NO. 5 MINE, BOREHOLE USBM-4 (*8*)

Borehole Completion

Borehole USBM-4 was drilled 6¼ in. in diameter to a depth of 597 ft. The only casing in the hole was 20 ft of 7⅝-in-diameter surface casing at the top of the hole. The hole was not cased to the coalbed because of the short time before anticipated mine-through of the borehole, which would preclude gas production; therefore, the expense of casing the hole did not seem justified. The Pittsburgh Coalbed was located at a depth of 588 to 594 ft for a total coal thickness of 6 ft. The total depth of the hole was 3 ft below the base of the Pittsburgh Coalbed. The immediate roof rock at the borehole was shale, and the floor rock was a calcareous shale. At the time of completion the borehole was 500 ft in advance of mining.

Treatment Implementation (April 17, 1974)

Borehole USBM-4 was treated through 2⅜-in-diameter tubing with an open hole packer set at 585 ft, 3 ft above the Pittsburgh Coalbed. The stimulation treatment record for this borehole is shown on figure 17. The treatment design to be implemented was to use gelled water and sand to create two fracture wings, each 387 ft long, of which 219 ft would be propped by a sand pack, 5 ft high and 0.22 in wide. A 2,000-gal gelled water pad was first injected into the coalbed to control leakoff. Formation break was reported at a surface pressure of 500 lbf/in^2(ga).

A pumping rate of 10.5 bbl/min was maintained throughout the treatment. Following the pad, an additional 5,300 gal of gelled water and 3,500 lb of 10/20-mesh sand (3,000 lb coated with fluorescent dye followed by 500 lb of uncoated sand) was injected into the coalbed according to the schedule shown in table 5. It should be noted that sand injection rates reported by Elder (*8*) in table 5 when totaled (2,637 lb) do not match the 3,500 lb

Table 5.—Summary of treatment chronology, borehole USBM-4 (*8*)

Fluid volume, gal	*Sand rate, lb/gal*
2,000 (pad)	NAp
1,300	0.25
650	.50
1,750	.75
1,350	.50
250 (flush)	NAp

NAp Not applicable.

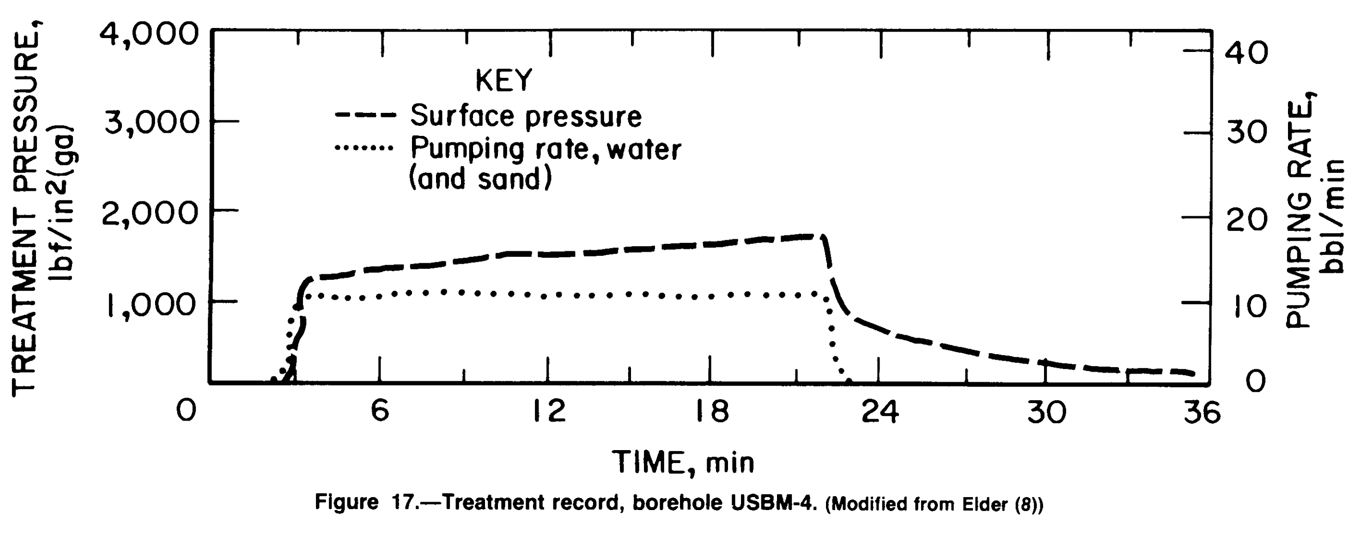

Figure 17.—Treatment record, borehole USBM-4. (Modified from Elder (*8*))

total sand weight reported in his text. The discrepancy may have resulted from inaccurate rates and/or volumes for the various stages as determined at the blender. A total of 7,300 gal of 75 lb per 1,000 gal gelled fluid was used in the treatment. Surface treatment pressures averaged about 1,550 lbf/in^2(ga) with a maximum surface pressure of nearly 1,800 lbf/in^2(ga) recorded.

Underground Observation

Borehole USBM-4 was mined through on June 12, 1974, approximately 2 months after stimulation. The area of the borehole intercept is shown in map view on figure 18. Elder (*8*) reported that approximately 20 ft of sand-filled vertical fracture was followed head-on as mining progressed to the east and then intercepted the borehole (location 1, figure 18). The fracture extended from the roof to floor and ranged from ⅛ to ½ in. in width (fig. 19). The fracture appeared to have propagated along face cleats with an orientation of N 70° W. The fracture was essentially vertical, but several small offsets where the fracture was diverted laterally along bedding planes in the coal gave an apparent inclination to the fracture. Three vertical sand-filled fractures invading butt cleats on a N 20° E azimuth were observed on the north rib approximately 2 ft from the borehole (location 2, figure 18). These fractures deviated short distances laterally on bedding planes, producing a stairstepping pathway that resulted in an arcuate pattern in gross appearance (fig. 20). The primary vertical fracture in the butt cleat direction was a maximum of 2½ in wide, and the two thinner fractures averaged approximately ½ in wide. The primary butt cleat fracture extended from roof to floor and the two thinner fractures extended from the roof and terminated before reaching the floor.

There was no apparent butt cleat fracture observed on the rib south of the borehole nor was there any face cleat fracture reported to the east of the borehole. The maximum extent of the butt cleat fracture into the northern rib is not known, but the maximum extent of 20 ft reported for the face cleat fracture is far short of the designed 219 ft of sand-propped fracture length. There were no roof penetrations or adverse mining conditions

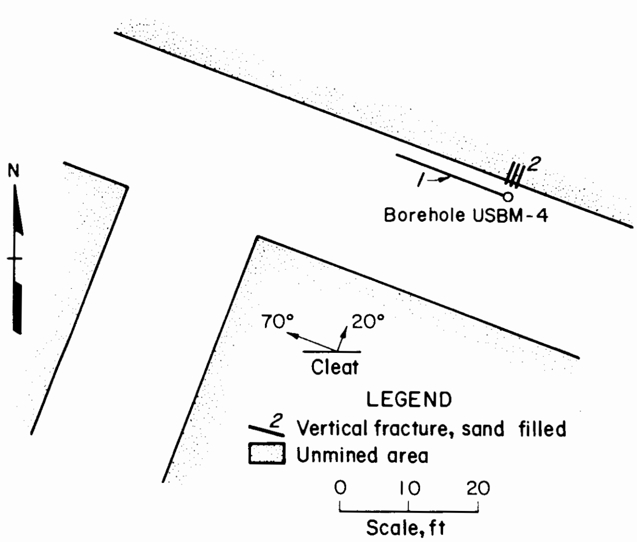

Figure 18.—Mine map, borehole USBM-4, with fracture orientations. (Modified from Elder (*8*))

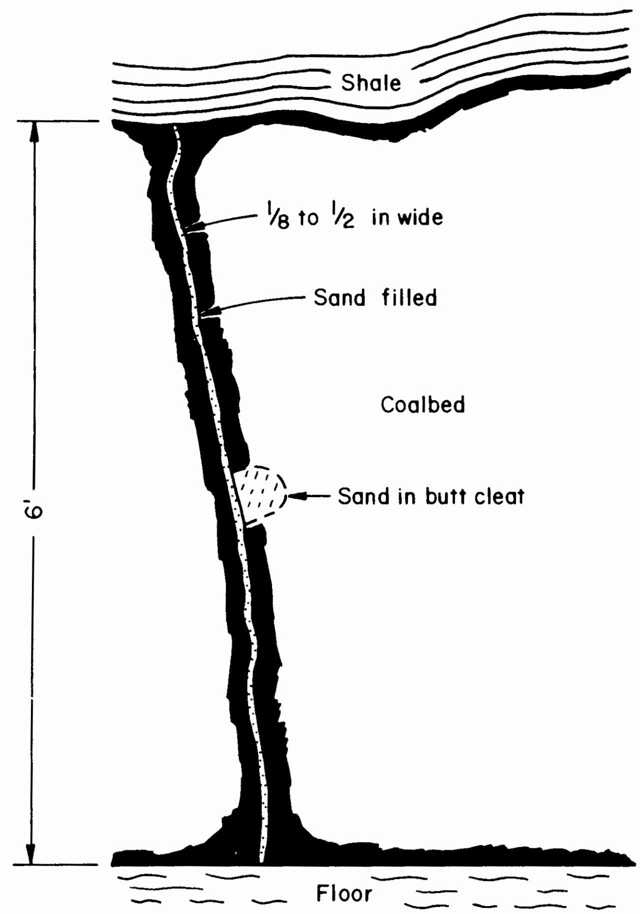

Figure 19.—Cross section of face cleat fracture in entry at location 1 near borehole USBM-4. (Modified from Elder (*8*))

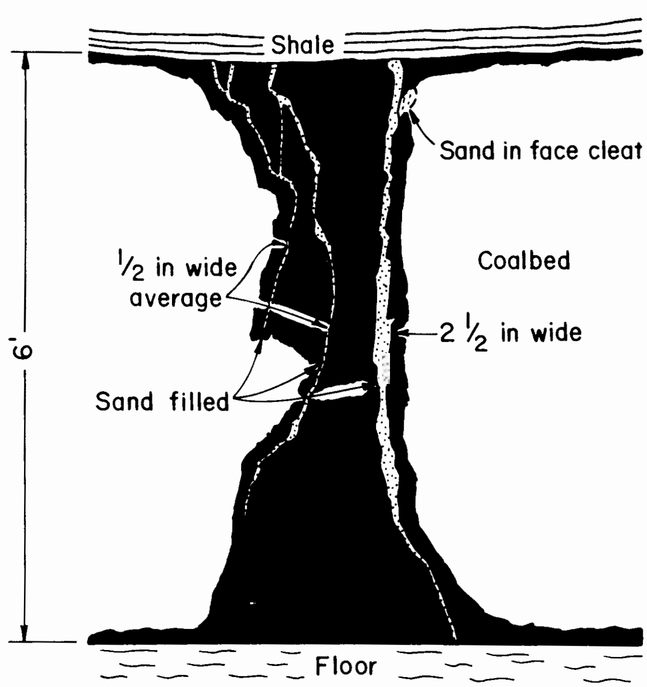

Figure 20.—Cross section of butt cleat fractures on rib at location 2 near borehole USBM-4. (Modified from Elder (*8*))

reported in the vicinity of borehole USBM-4. The site was revisited 2 yr after the initial mine-through, with no apparent roof or rib deterioration noted.

EMERALD MINE, BOREHOLE EM-5 (9-10)

Borehole Completion

Borehole EM-5 was drilled 6¼ in. in diameter to a depth of approximately 810 ft (40 ft below the Pittsburgh Coalbed) and cased with 4½-in-OD casing. The bottom of the casing was set in the shale above the target Pittsburgh Coalbed, and a formation packer shoe on the end of the casing was used to keep the cement from reaching the coalbed below. The coalbed was 6 ft thick and was located from 764 to 770 ft in the borehole. Prior to stimulation and production, the formation packer shoe was drilled out to provide communications with the coalbed below. At the time of completion, mining had not yet been initiated at the Emerald Mine. The borehole was located approximately 500 ft from the access shaft shown on figure 21.

Treatment Implementation (September 1, 1976)

Prestimulation strata characterization tests included gamma ray and neutron geophysical logs. A continuous stimulation treatment record is not available for this borehole. The treatment was initiated with a 900-gal water pad followed by 600 gal of 75-pct-quality nitrogen-generated foam. A formation breakdown pressure of 800 lbf/in^2(ga) was reported (*10*). A total of 31,500 gal of foam with 10,000 lb of sand (10/20- or 20/40-mesh) was injected into the coalbed. The average foam injection rate was 11.6 bbl/min, with the actual rate gradually increased as the sand rate was increased. The average surface treatment pressure was 1,375 lbf/in^2(ga). Gas production began relatively low but increased to a maximum of 117,000 ft^3/d after 7 months of production. The rate declined to 60,000 to 75,000 ft^3/d over the next several months. Details of the production history can be found in reference 10.

Underground Observations

A fracture wing from borehole EM-5 was intercepted by mining on July 21, 1978, approximately 2 yr after stimulation. The borehole location itself was not exposed by mining. The area of the fracture interception is shown in map view on figure 22. At the rib closest to the borehole, a single vertical sand-filled fracture up to 1½ in wide was observed extending from the floor to the roof (fig. 23). At the interface between the top of the coalbed and the overlying hard shale, the vertical fracture became horizontal. The sand-filled horizontal fracture was ⅛ to ¼ in wide, and at its maximum lateral extent was observed 50 ft from the presumed borehole location. The sand-filled vertical fracture could be traced across two entries of the mine, and at its maximum observed extent, it was approximately 140 ft from the presumed borehole location. The vertical fractures were propagated along face cleats, which averaged N 68° W in orientation. The width of the vertical sand-filled fracture varied from 1½ in at the exposure nearest the borehole to only a hairline at its maximum extent, where it was only partially filled with sand. No evidence of penetration of the roof strata was observed associated with the stimulation treatment at borehole EM-5.

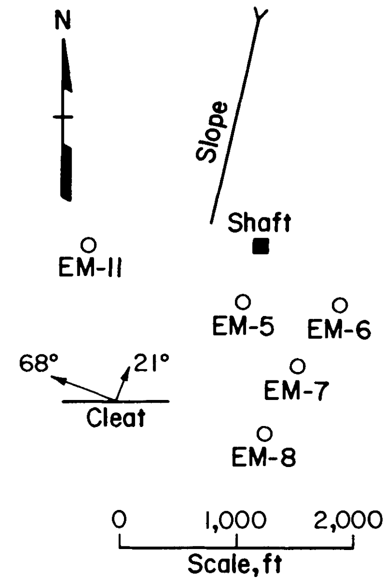

Figure 21.—Map of Emerald Mine area with locations of boreholes EM-5, EM-6, EM-7, EM-8, and EM-11. (Modified from Lambert (9))

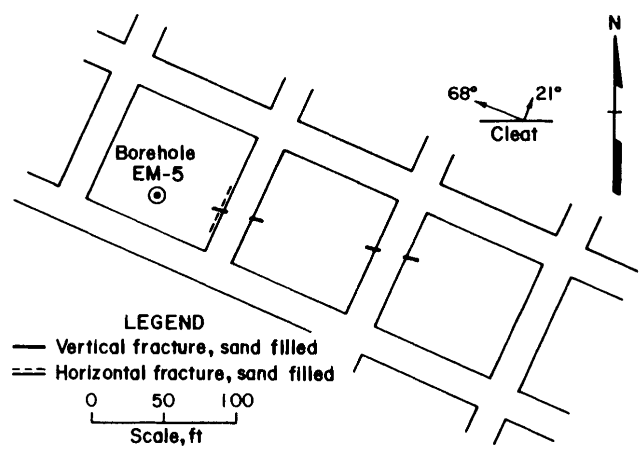

Figure 22.—Mine map, borehole EM-5, with fracture orientations. (Modified from Lambert (9))

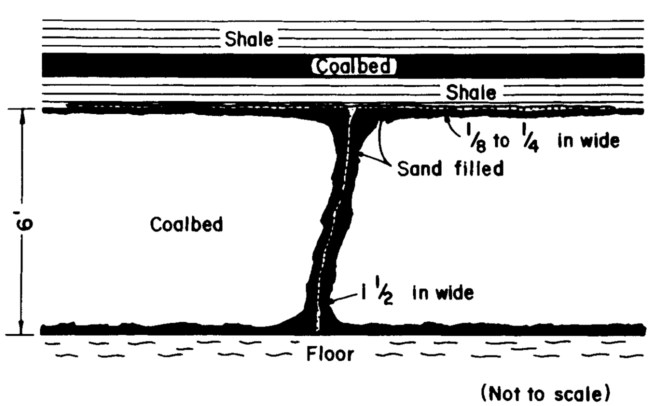

Figure 23.—Cross section of fractures on rib closest to borehole EM-5. (Modified from Lambert (9))

EMERALD MINE, BOREHOLE EM-6 (9-*10*)

Borehole Completion

Borehole EM-6 was drilled 6¼ in. in diameter to a depth of approximately 628 ft (40 ft below the base of the Pittsburgh Coalbed) and cased with 4½-in-OD casing. The bottom of casing was set in the shale above the target Pittsburgh Coalbed, and a formation packer shoe on the end of the casing was used to keep the cement from reaching the coalbed below. The coalbed was 6 ft thick and was located from 582 to 588 ft in the borehole. Prior to stimulation and production, the formation packer shoe was drilled out to provide communication with the coalbed below. At the time of completion, mining had not yet been initiated at the Emerald Mine. The borehole was located approximately 900 ft from the access shaft shown in figure 21.

Treatment Implementation (April 15, 1976)

Prestimulation strata characterization tests included gamma ray and neutron wireline geophysical logs. The continuous stimulation treatment record for this borehole is shown in figure 24. The treatment was initiated with a 900-gal water pad followed by 600 gal of 75-pct-quality nitrogen-generated foam. A formation break pressure of 950 lbf/in²(ga) was reported. A total of 29,200 gal of foam with 14,000 lb of sand (10/20- or 20/40-mesh) was injected into the coalbed.

The average foam injection rate was 17.7 bbl/min, with the actual rate gradually increasing as the sand rate increased. The average surface treating pressure was 1,500 lbf/in²(ga). It was reported by Steidl (*10*) that a screenout occurred near the planned end of the treatment causing only a slightly premature termination of the stimulation. Maximum surface pressure of about 2,150 lbf/in²(ga) was reached at the start of sand injection and again at the end of the treatment when the screenout was reported.

Gas production was generally erratic in the beginning, however, a maximum rate of 110,000 ft³/d was reported 1 yr after production began. The rate gradually declined to near 25,000 ft³/d at the termination of production prior to mine-through. Details of the production history can be found in references 9 and 10.

Underground Observations

Borehole EM-6 was mined through on November 9, 1978, approximately 2½ yr after stimulation. The area of the borehole interception is shown in map view in figure 25. A single vertical sand-filled fracture, approximately 2½ in wide and extending from the base of the coalbed to a point about 3 ft above the base was observed on the west rib, 10 ft away from the intercepted borehole (fig. 26). The vertical fracture was propagated along face cleats and several discontinuous sand-filled fractures extended to the top of the main coal bench. Several additional thin discontinuous sand-filled vertical fractures paralleled the main fracture and were also developed in face cleats. The average orientation was N 68° W. One of the short vertical fractures penetrated the thin roof shale above the main coal bench and terminated at the base of the rider coal.

An inclined fracture split off from the main vertical fracture and stairstepped its way up to the top of the coalbed where it became horizontal for a short distance before inclining through the thin (8-10 in) roof shale and finally becoming horizontal at the base of the rider coal. The sand-filled horizontal fracture on top of the main coal bench was about ½ in thick and the horizontal fracture at the base of the rider coal was ¼ to ½ in thick. No additional exposures were observed for the fractures seen on the ribs adjacent to the borehole. The extent of the fractures into the ribs is unknown. No adverse mining conditions were encountered due to the penetration of the

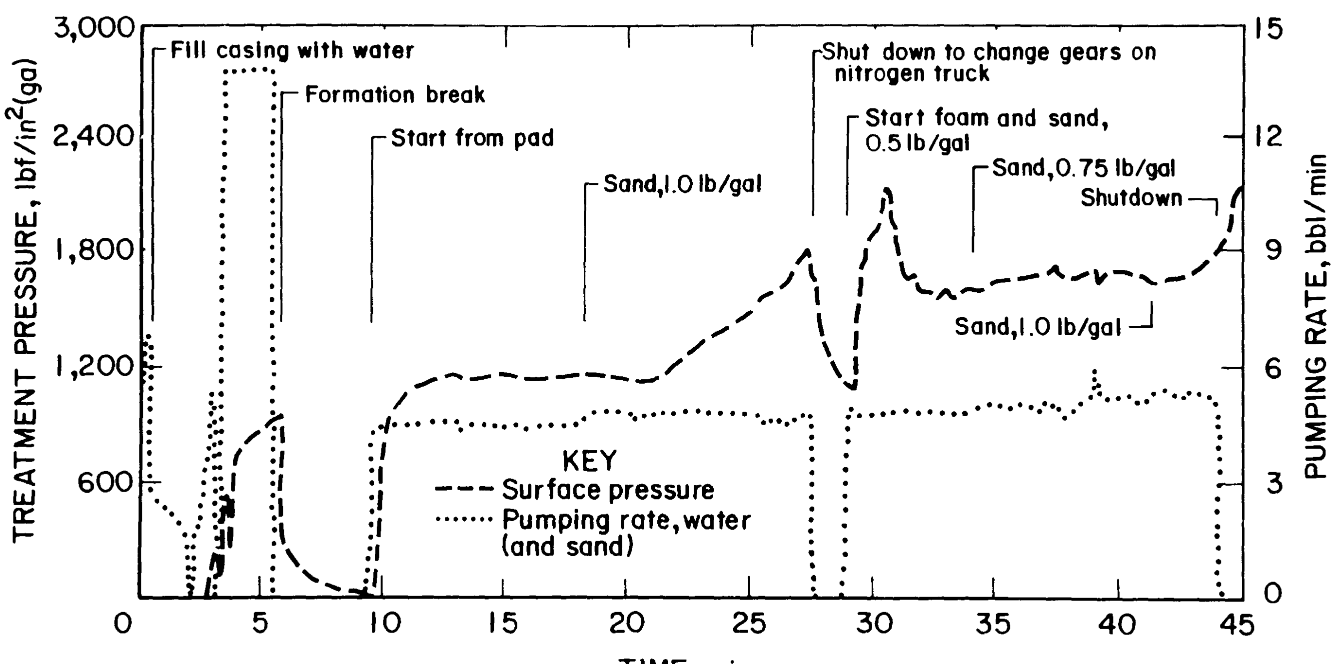

Figure 24.—Treatment record, borehole EM-6.

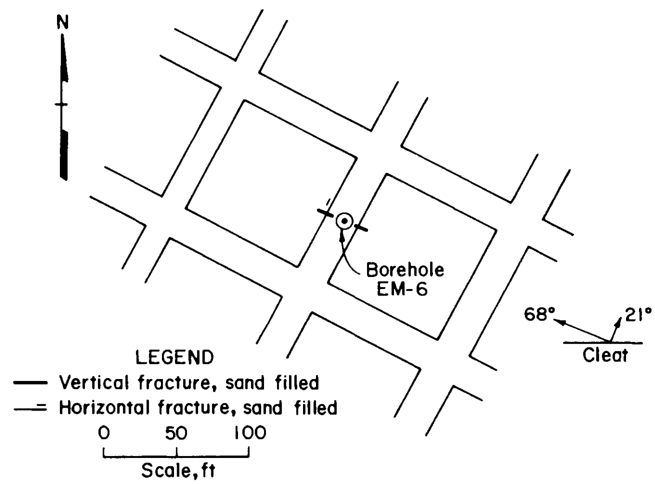

Figure 25.—Mine map, borehole EM-6, with fracture orientations. (Modified from Lambert (9))

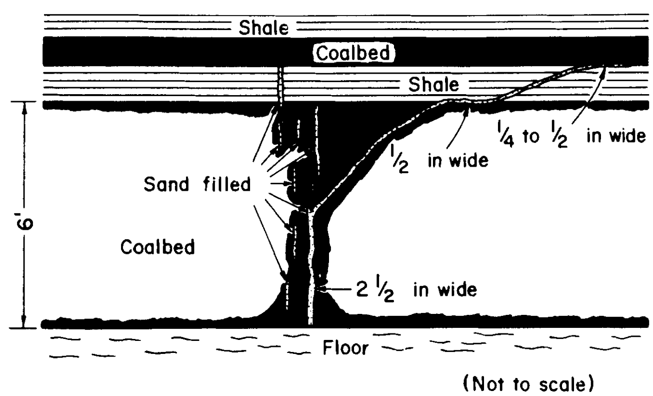

Figure 26.—Cross section of fractures on rib west of borehole EM-6. (Modified from Lambert (9))

strata overlying the main bench of the Pittsburgh Coalbed. In fact, common mining practice at the mine has been to extract the thin roof shale and part of the rider coal leaving a thin interval of the rider coal as the actual mine roof.

EMERALD MINE, BOREHOLE EM-7 (9-*10*)

Borehole Completion

Borehole EM-7 was drilled 6¼ in. in diameter to a depth of approximately 774 ft (40 ft below the base of the Pittsburgh Coalbed) and cased with 4½-in-OD casing. The bottom of casing was set in the shale above the target Pittsburgh Coalbed, and a formation packer shoe on the bottom of the casing was used to keep the cement from reaching the coalbed below. The coalbed was 6 ft thick and was located from 728 to 734 ft in the borehole. Prior to stimulation and production, the formation packer shoe was drilled out to provide communication with the coalbed below. At the time of completion, mining had not yet been initiated at the Emerald Mine. The borehole was located approximately 1,100 ft from the access shaft shown in figure 21.

Treatment Implementation (September 8, 1976)

Prestimulation strata characterization tests included gamma ray and neutron wireline geophysical logs. A continuous stimulation treatment record is not available for this borehole. The treatment was initiated with a 900-gal water pad followed by 600 gal of 75-pct-quality nitrogen-generated foam. A formation break pressure was not reported. A total of 29,000 gal of foam with 7,400 lb of sand (10/20- or 20/40-mesh) were injected into the coalbed. The average foam injection rate was 10.8 bbl/min, with the actual rate gradually increasing as the sand rate increased. The average surface treatment pressure was 1,400 lbf/in^2(ga). It was reported by Steidl (*10*) that a screenout occurred near the planned end of the treatment causing only a slightly premature termination of the stimulation. Gas production from the borehole began very high (120,000 ft^3/d) reaching a maximum of 140,000 ft^3/d after only 1 month of production. The rate eventually declined to about 6,000 ft^3/d at the termination of gas production prior to mine-through. Details of the production history can be found in references 9 and 10.

Underground Observations

Borehole EM-7 was mined through on December 1, 1978, approximately 2¼ yr after stimulation. Vertical sand-filled fractures, ¼ to ½ in wide, were reported a maximum of 18 ft laterally from the borehole. No horizontal fractures were present nor was there any penetration of strata above the main bench of the Pittsburgh Coalbed.

EMERALD MINE, BOREHOLE EM-8

Borehole Completion (*10*)

Borehole EM-8 was drilled 6¼ in. in diameter to a depth of approximately 692 ft (40 ft below the base of the Pittsburgh Coalbed) and cased with 4½-in-OD casing. The bottom of the casing was set in the shale above the target Pittsburgh Coalbed, and a formation packer shoe on the end of the casing was used to keep the cement from reaching the coalbed below. The coalbed was 6 ft thick and was located from 646 to 652 ft in the borehole. Prior to stimulation and production, the formation packer shoe was drilled out to provide communication with the coalbed below. At the time of completion, mining had not yet been initiated at the Emerald Mine. The borehole was located approximately 1,600 ft from the access shaft shown on figure 21.

Treatment Implementation (September 15, 1976) (*10*)

Prestimulation strata characterization tests included gamma ray and neutron wireline geophysical logs. The continuous stimulation treatment record for this borehole is shown in figure 27. The treatment was initiated with a 900-gal water pad followed by 600 gal of 75-pct-quality nitrogen-generated foam. A formation break was not reported. A total of 42,000 gal of foam with 12,800 lb of sand (10/20- or 20/40-mesh) were injected into the coalbed. The average foam injection rate was 10.8 bbl/min, with

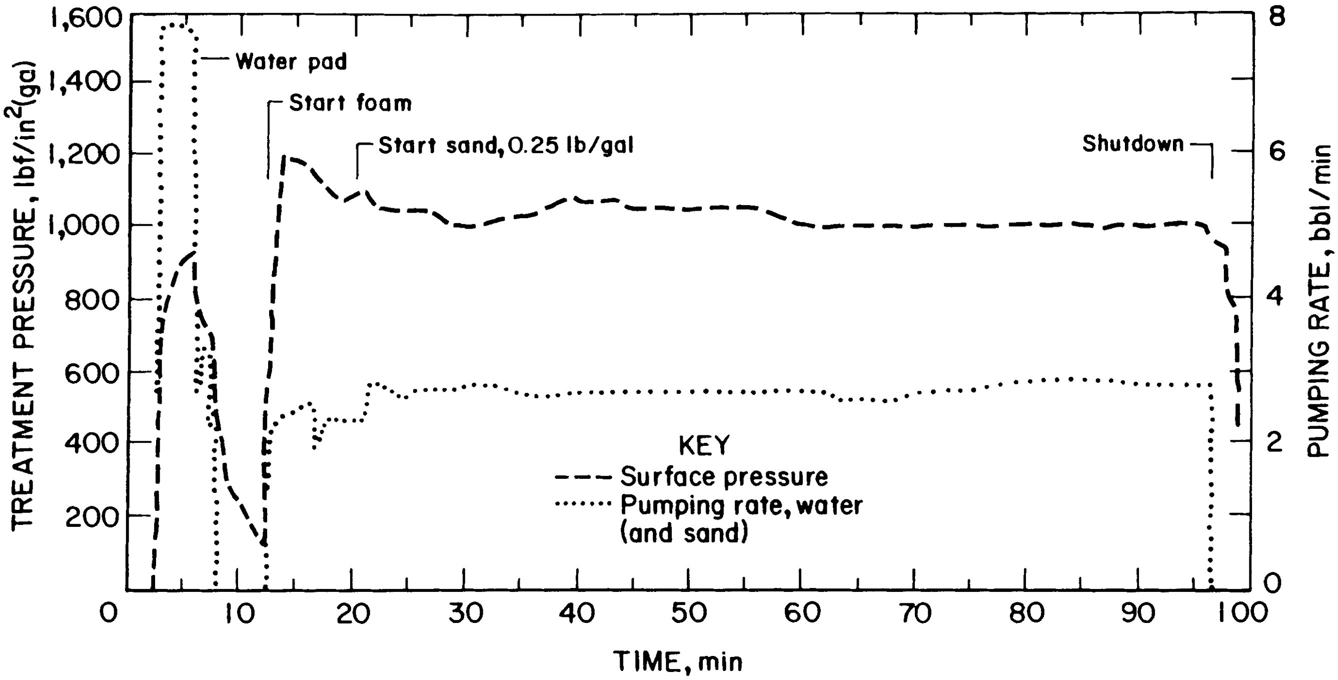

Figure 27.—Treatment record, borehole EM-8.

the actual rate gradually increasing as the sand rate increased. The average surface treatment pressure was 1,050 lbf/in²(ga). Gas production from borehole EM-8 was never very high, with the maximum rate of 21,000 ft³/d being achieved approximately 1 month after stimulation. The rate eventually declined to only 2,000 ft³/d prior to the termination of gas production just before mine-through. Details of the production history can be found in reference 10.

Underground Observations

The area around borehole EM-8 was mined through in the spring of 1979, approximately 2½ yr after stimulation. A detailed underground investigation was not conducted until the summer of 1985 when the authors of this report visited the site. Vertical sand-filled fractures were observed at four locations on the eastern rib of the pillar presumed to contain the borehole (fig. 28). At location 1, the sand-filled fracture extended approximately 3.8 ft into the main bench of the coalbed from the top (fig. 29). At the top of the coalbed the fracture was 1/16 in wide and tapered to only the width of a single sand grain at the bottom. The fracture was propagated along a face cleat with an orientation of N 65° W. The fracture penetrated up into the shale above the main bench where it intercepted and propagated along an inclined fracture which was about 1/16 in wide. A second inclined fracture close to and nearly parallel to the first was also filled with sand. Both of these fractures terminated at the top of the shale, at the interface with the overlying rider coal. The two inclined fractures in the thin (0.9 ft) shale were very similar in appearance to other non-sand-filled naturally occurring fractures in the area, and are assumed to have existed prior to and been invaded by the stimulation treatment. A second short vertical sand-filled fracture, one sand grain thick, extended down from the top of the coalbed approximately 1 ft into the coalbed at location 1.

No adverse mining conditions were reported nor were deteriorated roof conditions observed at this location, even after exposure of the fracture for 6 yr. As noted earlier, the common mining height at this mine includes the shale unit that was penetrated by the stimulation treatment.

The vertical sand-filled fracture at location 2 (fig. 30) was contained in the lower 2 ft of the coalbed and turned horizontal above a distinctive bony coal band. The vertical fracture also stairstepped short distances along bedding planes in the coalbed before turning completely horizontal. The vertical fracture was 1/16 in wide and was the same thickness but discontinuous after turning horizontal. The vertical fracture was contained in a face cleat with an orientation of N 72° W. There also seemed to be a sand-filled butt cleat fracture at this location, but the exposure was such that it could not be conclusively delineated.

At location 3, two short (1½-ft) en echelon sand-filled vertical fractures extended from the roof approximately 3 ft down into the coalbed (fig. 31). The upper fracture was 1/16 in wide near the top and widened to 1/8 in at the bottom. The second fracture was 1/8 in wide at the top and narrowed to 1/16 in at the bottom. Both fractures were propagated along face cleats with an orientation of N 66° W. No roof penetration or horizontal fractures were observed at this location.

At location 4, a sand-filled fracture was essentially vertical but did stairstep short distances on horizontal bedding planes in the coal (fig. 32). Above the distinct shale bands the fracture was about 3/16 in wide, and narrowed slightly to 1/8 in below the shale bands. The fracture extended from the floor to the top of the coalbed, and penetrated 0.15 ft into the overlying shale. No adverse mining conditions were experienced as a result of this minor penetration of the thin shale bed. The fracture at this location was predominately propagated along face cleats with an orientation of N 67° W. Short sand-filled butt cleat fractures were also observed. This location, at 55 ft, was the maximum observed extent of a vertical fracture from the presumed location of the borehole. No horizontal fracture was present at this location.

An extensive investigation of the pillars surrounding the one presumed to contain the borehole did not reveal any additional vertical fractures. Even though only minor exposures of butt cleat fractures were observed, a substantial portion of the fracture must have stairstepped along the butt cleat because it is otherwise impossible to extend the four nearly parallel face cleat oriented fractures back to the presumed location of the borehole.

Horizontal fractures were observed at several locations, generally to the south of the borehole (fig. 28). The fractures were found on horizontal bedding planes in the thin shale below the rider (above the main bench), and on the shale-coal interface above and below the rider coal. At some locations, horizontal sand-filled fractures could be found on more than one of the described horizontal surfaces. The fractures ranged from 3/16 in to essentially only a single sand grain in thickness. The maximum distance a horizontal sand-filled fracture was observed from the presumed location of the borehole was 115 ft.

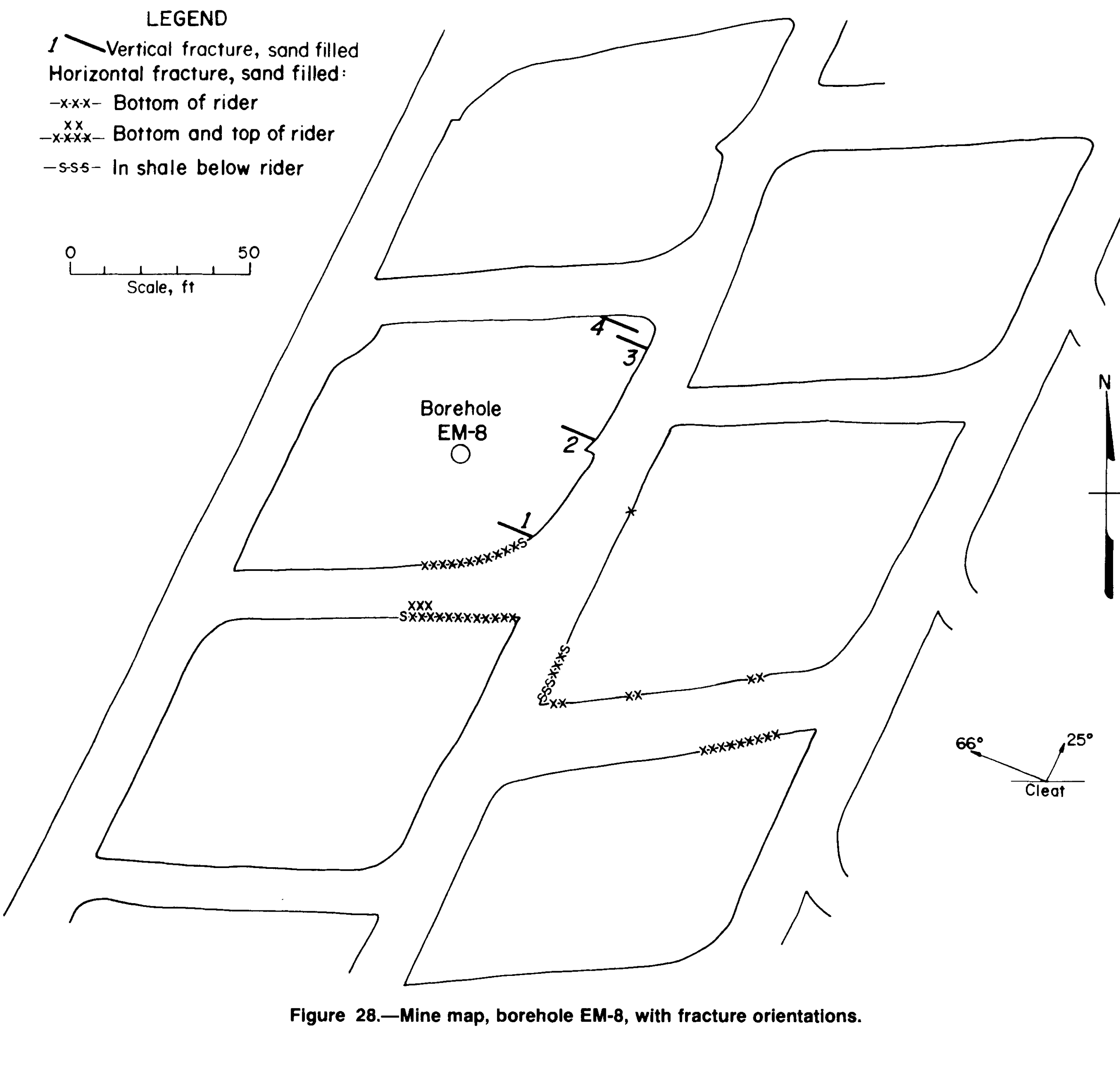

Figure 28.—Mine map, borehole EM-8, with fracture orientations.

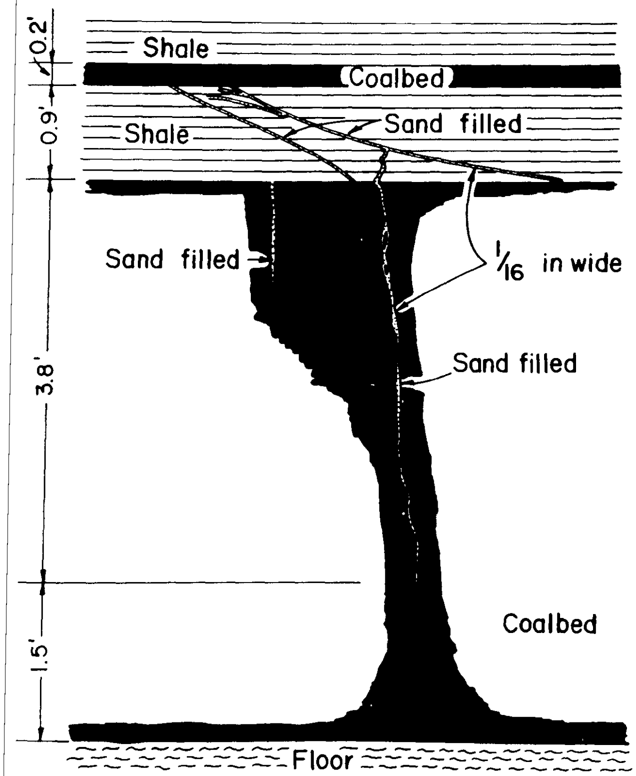

Figure 29.—Cross section of fractures on rib at location 1 near borehole EM-8.

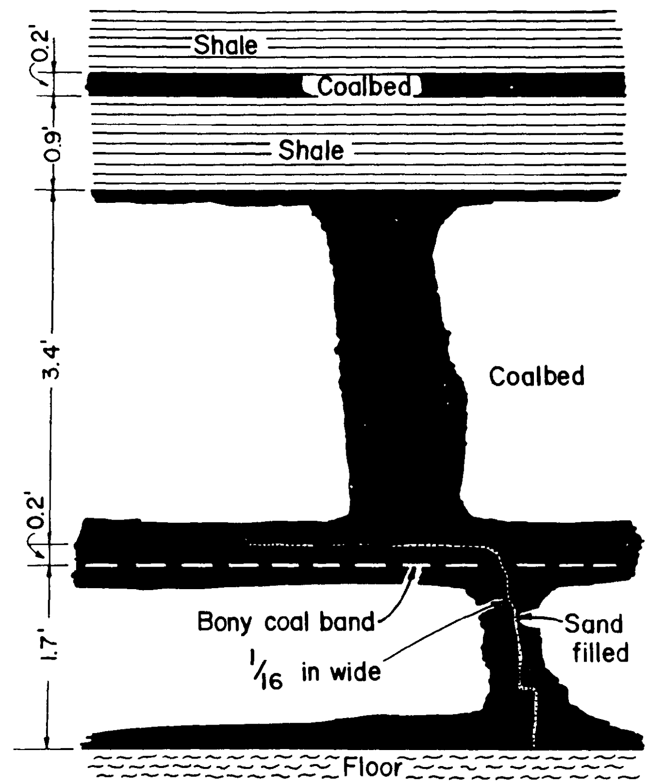

Figure 30.—Cross section of fractures on rib at location 2 near borehole EM-8.

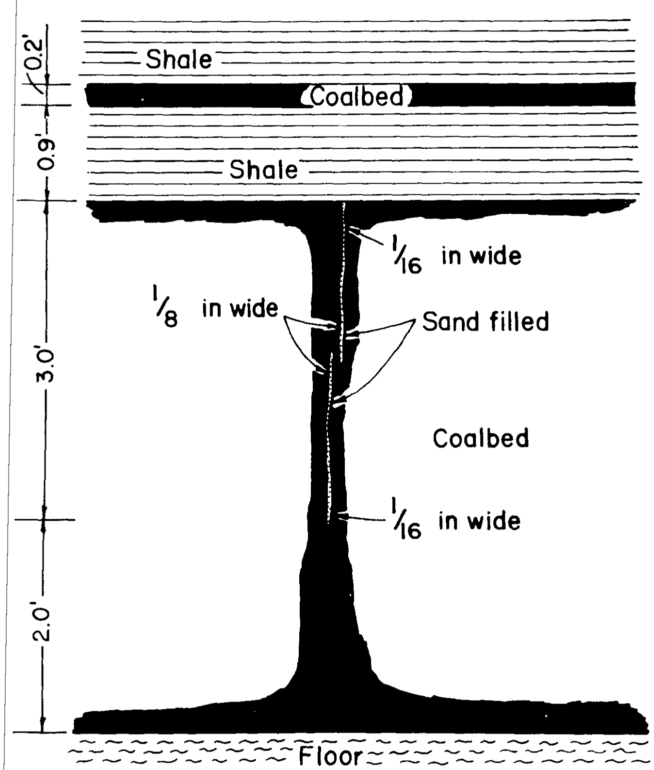

Figure 31.—Cross section of fractures on rib at location 3 near borehole EM-8.

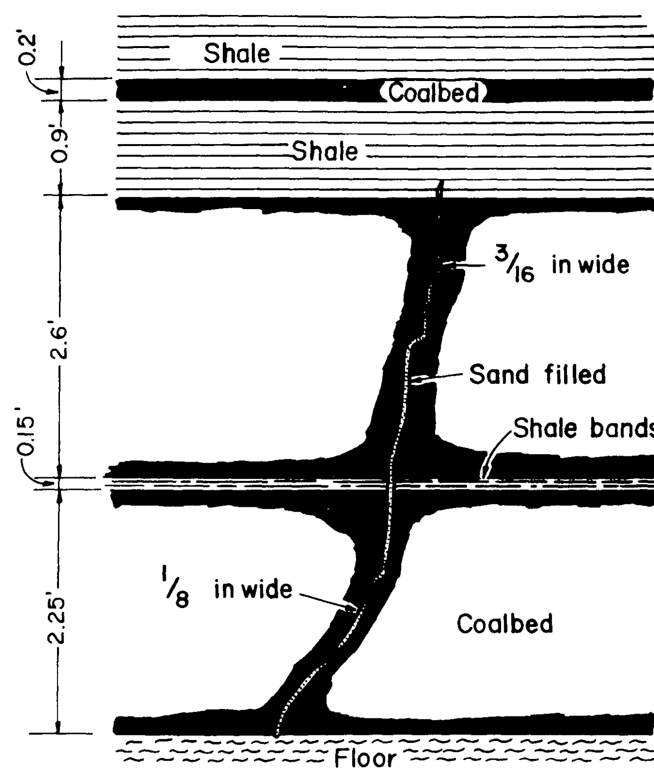

Figure 32.—Cross section of fracture on rib at location 4 near borehole EM-8.

EMERALD MINE, BOREHOLE EM-11 (9)

Borehole Completion

Borehole EM-11 was drilled to a depth of 725 ft, 6 ft below the base of the 6-ft-thick Pittsburgh Coalbed. The top of the coalbed was at a depth of 713 ft. The hole was cased and cemented to the top of the coalbed. At the time of completion, little mining had been completed at the Emerald Mine. The borehole was located approximately 1,000 ft from the bottom of the slope shown in figure 21.

Treatment Implementation (May 14, 1977)

Borehole EM-11 was stimulated with a patented treatment called a Kiel Frac (*23*). This treatment technique utilized multiple pressurization-depressurization cycles that would theoretically create long vertical fractures along transverse directions, then prop the fractures with reservoir rock material that sloughs off during the treatment. The treatment fluid was water with 80/100- and 20/40-mesh sand. The sand was added primarily to control fluid loss. In addition, the patent (*23*) claims that "the fracture formed in the producing formation may be confined to the upper portion of the producing formation where lithology (overlying rock) will limit upward growth of the fracture and sand properly scheduled will limit the downward growth of the fracture."

The treatment on borehole EM-11 used over 54,600 gal of water, injected at a rate of about 19 bbl/min, and 10,000 lb of sand proppant. Surface pressures during the pressurization cycles averaged about 1,200 lbf/in^2(ga). A continuous treatment record is not available for this borehole. Gas production from this borehole began relatively high (over 40,000 ft^3/d) and reached a maximum of almost 87,000 ft^3/d within a month after production began. The production rate gradually declined to 3,000 ft^3/d prior to termination of production before mine-through.

Underground Observations

Sand-filled fractures from borehole EM-11 were intercepted in June of 1978, approximately 1 yr after stimulation. The borehole was not mined through. The area of the fracture interception is shown in map view in figure 33. The only observed fractures were horizontal to slightly inclined and were located in the rider coal above the main bench of the Pittsburgh Coalbed (fig. 34). One of the fractures curved up into the shale overlying the rider coal.

The penetration of the upper shale bed at this location may have been influenced by the presence of a clay vein. Clay veins are commonly characterized by planes of weakness at their interface with surrounding strata. The location of the exposures of horizontal fractures was approximately 110 ft from the presumed location of the borehole. No other exposure of sand-filled fractures was observed, and no adverse mining conditions were reported related to the presence of the horizontal fractures in the rider coal, which is commonly mined along with the main bench. Since borehole EM-11 was not completely mined around, additional sand-filled fractures may have been created, but not mined through. Vertical fractures that would have extended from the borehole in the face cleat direction could have been intercepted by the mine

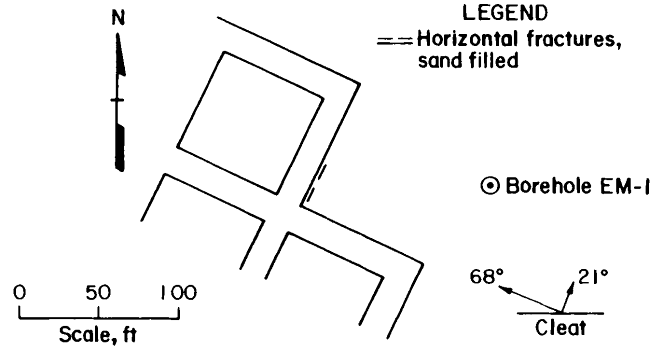

Figure 33.—Mine map, borehole EM-11, with fracture orientations. (Modified from Lambert (9))

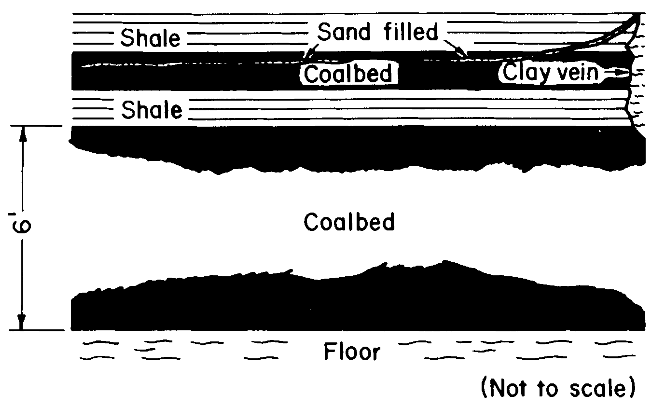

Figure 34.—Cross section of fractures on rib near borehole EM-11. (Modified from Lambert (9))

development available for inspection, unless significant stairstepping (as the Kiel Frac was specifically supposed to accomplish) along the butt cleats had occurred.

CUMBERLAND MINE, BOREHOLE CNG-1034

Borehole Completion (*24*)

Borehole CNG-1034 was drilled 7⅞ in. in diameter to a depth of 825 ft, a point 63 ft below the base of the Pittsburgh Coalbed. The target Pittsburgh Coalbed was 8 ft thick and located from 754 to 762 ft in the borehole. The hole was cased with 5½-in-OD casing to a depth of 755 ft, 1 ft into the top of the coalbed. A retrievable packer was set to prevent cement infiltration into the coalbed below casing. The distance from the borehole to active mining is not known.

Treatment Implementation (May 5, 1977) (*24*)

Prestimulation strata characterization tests included natural gamma ray, density, neutron, temperature, and caliper wireline geophysical logs along with a driller's log and drilling time log. The hole was stimulated with 75-pct-quality nitrogen-generated foam with sand proppant. Prior to the stimulation treatment a mixture of Cal-seal[4] and ¾-in limestone chips was used to fill the

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

bottom of the hole below the Pittsburgh Coalbed to keep the treating fluids from invading the strata below. The treatment was initiated by pumping a 2,000-gal foam pad at a rate of 10 bbl/min. A formation break at 800 lbf/in²(ga) surface was reported for this treatment. A continuous stimulation treatment record is not available for this borehole, but a summary of the general treatment chronology is presented in table 6.

Table 6.—Summary of treatment chronology, borehole CNG-1034 (*24*)

Foam vol,[1] gal	Sand		
	Rate, lb/gal	Size	Weight, lb
2,000 (pad)	NAp	NAp	NAp
2,000	0.5	Minus 100 mesh	1,000
2,000	1.0	.. do	2,000
4,000	1.0	20/40 mesh	4,000
10,000	1.5	.. do	15,000
1,000	1.5	.. do	[2]1,500
840 (flush)	NAp	NAp	NAp

NAp Not applicable.
[1]Constant injection rate of 10 bbl/min.
[2]Dye coated.

Foam was injected at a constant rate of 10 bbl/min throughout the treatment, with sand added at an initial rate of 0.5 lb/gal and gradually increased in 0.5-lb/gal increments to a maximum rate of 1.5 lb/gal. Minus 100-mesh sand was added at the beginning of the treatment as a fluid loss agent before the 20/40-mesh sand was added as a proppant. Near the end of the treatment, 1,500 lb of dye-coated sand was added to the stimulation fluid. A total of 21,840 gal of foam, 640 gal of water (flush at end), and 23,500 lb of sand were used in the stimulation treatment. The average surface treatment pressure was reported to be 1,200 lbf/in²(ga). The computer-designed treatment was to propagate a vertical fracture with a length of 2,764 ft. Gas production from this hole was low, with the maximum rate of 5,400 ft³/d reported approximately 1 month after stimulation.

Underground Observations (*19*)

Fractures from borehole CNG-1034 were intercepted in 1981, approximately 4 yr after stimulation. A vertical fracture filled with sand was observed 85 ft to the east of the presumed location of the borehole (fig. 35). The fracture extended from the floor to the roof along face cleat

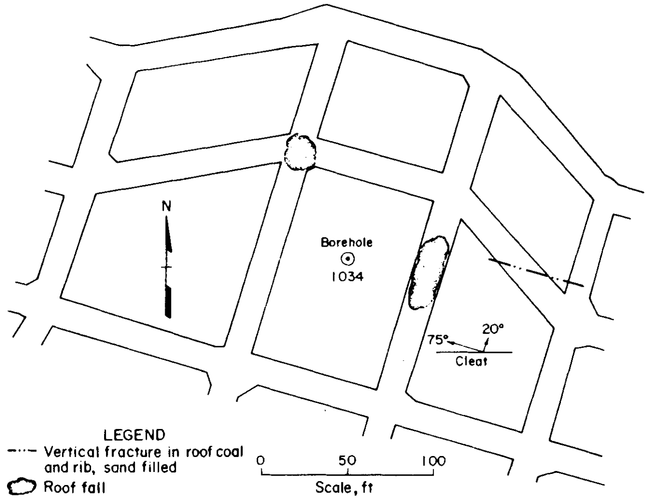

Figure 35.—Mine map, borehole CNG-1034, with fracture orientations (*19*).

and varied in width from 1/8 to 1/4 in. The fracture could be traced in the roof coal across the entry in the face cleat direction to where it was exposed as a vertical fracture on the corner of the opposite rib. The fracture continued through the corner of the rib, exiting on the opposite side. The fracture could be traced an additional 10 ft across the entry in the roof coal, approximately 130 ft from the presumed location of the borehole. No penetration of the strata above the coalbed was reported along the exposed length of the fracture.

The entry adjacent to the pillar that contained the borehole would also be expected to contain an exposure of the fracture since it is closer to the borehole than the exposures previously described, however, a roof fall in this entry prevented direct observation of the area. Investigation of the roof fall revealed that it appeared to be related to a "roll" in the roof, which was characterized by highly disturbed bedding and abundant slickensided surfaces that characteristically have a lack of cohesiveness. Roof falls associated with similar geologic conditions are common at the mine site, therefore, the mine company personnel did not attribute the roof fall to the stimulation treatment. No evidence of a vertical fracture wing was seen to the west-northwest of the borehole, nor were any horizontal fractures reported at any location.

UPPER FREEPORT COALBED, PENNSYLVANIA

LUCERNE NO. 6 MINE, BOREHOLE RP-1 (*12*)

Borehole Completion

Borehole RP-1 was drilled with air, 7 in. in diameter to a depth of 675 ft, approximately 42 ft below the base of the target Upper Freeport Coalbed. The coalbed was 6.75 ft thick with a 5-in-thick shale parting near the top of the coal interval, and was located from 626.5 to 633.25 ft in the borehole. Prior to casing the borehole, sand was used to fill the hole to the top of the coalbed as an extra precaution against cement penetrating the coal interval. The borehole was cased with 4½-in-OD casing with a cement basket shoe on the bottom as the primary means of keeping cement from reaching the coalbed below the casing. The bottom of casing was set at 622 ft, 4.5 ft above the top of the coalbed. The bottom of casing was to be set closer to the top of the coalbed, but debris from running the casing fell on top of the sand pack preventing the casing from reaching the desired depth. The basket shoe and sand pack were drilled out to a depth of about 2 ft below the base of the coalbed in preparation for stimulation.

Treatment Implementation (January 21, 1982)

Prestimulation strata characterization tests on this borehole were quite extensive. Gamma ray and density wireline geophysical logs were obtained prior to casing the borehole. A series of in situ state of stress (ISSOS) tests were made in the borehole prior to setting casing. The ISSOS test is essentially a "ministimulation" treatment that introduces a small amount of fluid into isolated zones in the wellbore to determine a "breakdown" pressure and instantaneous shut-in pressure.

An ISSOS test in the roof rock above the coalbed (616 to 624 ft) produced two formation breaks, one at slightly less than 800 lbf/in²(ga) bottom hole and a second at about 1,600 lbf/in²(ga) bottom hole. The first break was interpreted to be a vertical fracture and the second a horizontal fracture (*25*). An instantaneous shut-in pressure (ISIP) of 750 lbf/in²(ga) bottom hole was recorded. No definitive formation break was recorded for the coalbed interval tested (626 to 634 ft); the ISIP was only 490 lbf/in²(ga) bottom hole, which was also the maximum pressure recorded during the test.

A series of mechanical property tests including triaxial compressive strength, Young's modulus, and residual friction angles and coefficients were conducted on coal and surrounding rocks from the mine site (*25*). In general, the rock was found to have a higher strength than the coal. A stimulation treatment would be expected to stay in the coalbed if higher stress and/or higher strength rocks surrounded it, and the treatment pressures are only allowed to barely exceed the pressure necessary to "break" the coalbed. In this case, a high enough differential between the ISSOS test values and the laboratory derived strength data would appear to be present to keep the stimulation treatment in the coalbed if the treatment pressure was kept near the 490-lbf/in²(ga) bottom hole ISIP value of the coalbed.

The treatment for borehole RP-1 was to be very small, using only 2,775 gal of 75-pct-quality nitrogen-generated foam (injected at a rate of 5 bbl/min) and 1,360 lb of 20/50-mesh sand proppant. The treatment was small because the hole was located only 250 ft from mining. The computer-designed treatment would have theoretically produced two sand-filled fracture wings each extending for a distance of 209 ft from the borehole. The coalbed was not jet slotted prior to the stimulation since it was presumed to have already been fractured during the ISSOS test.

During the initial stage of the treatment, while using clear water to initiate a fracture in the coal, treatment pressures steadily climbed and remained high. The continuous stimulation treatment record is shown on figure 36. Several cycles of pressure buildup and release

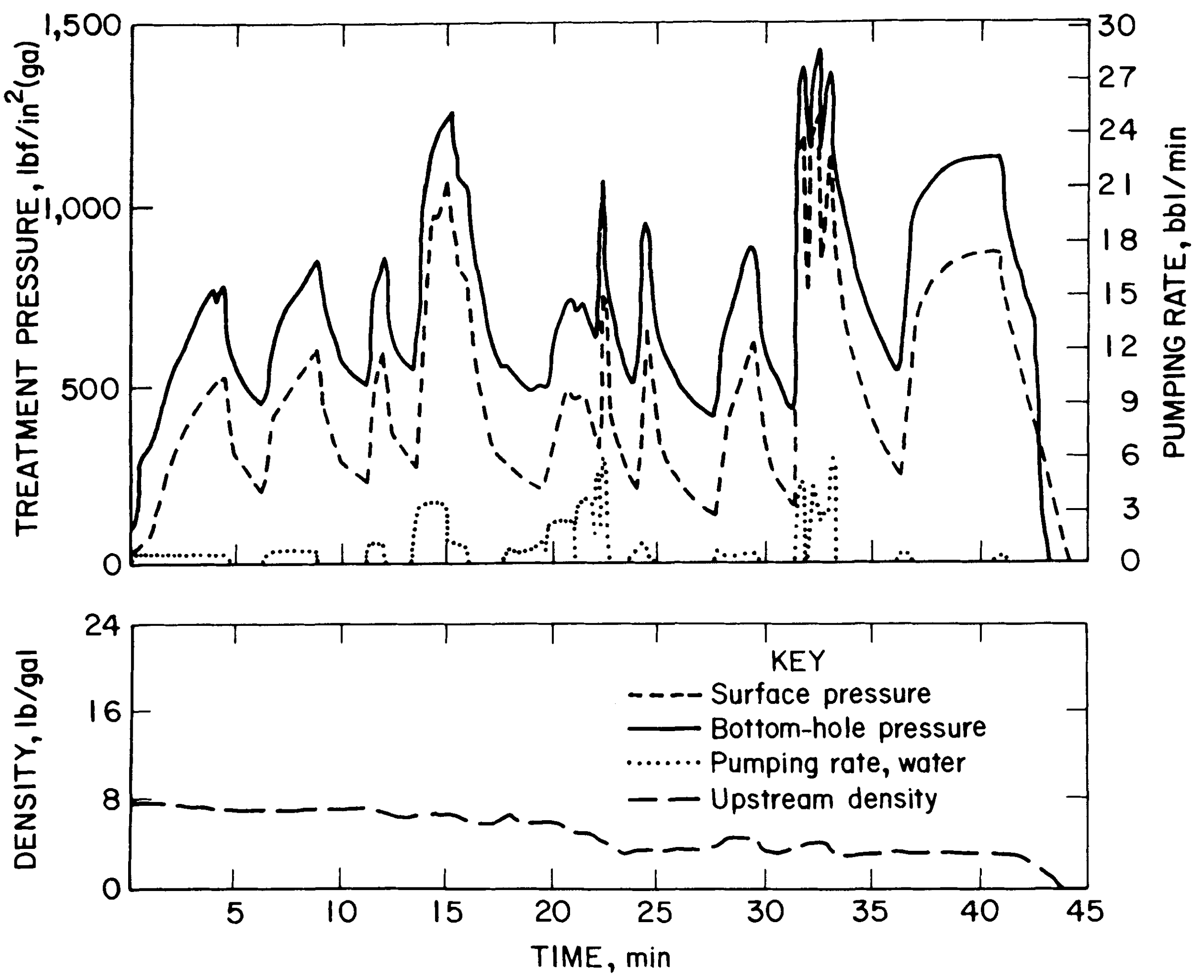

Figure 36.—Treatment record, borehole RP-1.

were made in an attempt to initiate a fracture, without success. A total of 1,600 gal of clear water containing green fluorescent paint was injected into the coalbed at rates ranging from 0.4 to 7.4 bbl/min. No sand proppant was included in the injected fluid. Maximum treatment pressures of 1,450 lbf/in^2(ga) bottom hole and 1,260 lbf/in^2(ga) surface were reached. Table 7 summarizes parameters for the stimulation.

Table 7.—Summary of treatment chronology, boreholes RP-1 through RP-3 (*12*)

Borehole and pigment color	Treatment	
	Stage	Vol, gal
RP-1: Green	Water pad	1,600
RP-2:		
Blue	Foam pad	10,000
Orange	Foam and 0.5 lb/gal sand	4,400
Yellow	Foam and 0.5 to 1.0 lb/gal sand	5,400
RP-3:		
Red	Foam pad	20,000
Blue	Foam and 0.5 lb/gal sand	2,500
Orange	Foam and 1.0 lb/gal sand	1,600
Yellow	Foam and 1.5 lb/gal sand	6,100

The borehole (plus boreholes RP-2, RP-3, KE-2, and SC-1 to be discussed later) was not completed for production since the project goals (BuMines contract J0333908) were only to stimulate and evaluate the effect of the stimulation treatment on the coalbed and surrounding strata.

Underground Observations

Borehole RP-1 was mined through on February 12, 1982, less than 1 month after stimulation. The borehole was found approximately 25 ft from the expected location determined by a deviation survey. Extensive mapping of existing geologic conditions was conducted near this borehole and the two companion boreholes (RP-2 and RP-3) prior to the stimulation and mine-through, to aid in interpreting the effect of the treatment on the coalbed and surrounding strata. A complete geologic interpretation of the area surrounding the three boreholes completed at this mine site can be found in the contract final report (*12*). Many visits were also made to the area expected to be influenced by the treatments as mining progressed towards the boreholes, so that any exposures on the advancing faces that would be lost by the continual advance would be documented. These multiple site visits, the use of fluorescent paint in the treatments, and the extensive mining around the three boreholes at the Lucerne No. 6 Mine make the underground characterizations (along with those of borehole TW-5 at the Oak Grove Mine) the most complete of the stimulation treatments observed.

Vertical fractures (**25**)[5] from borehole RP-1 were found in the southeast rib adjacent to the intercepted borehole (fig. 37). Nine vertical fractures in a zone 8½ in

[5]Boldface numbers in parentheses refer to labeled fracture traces in figure 37.

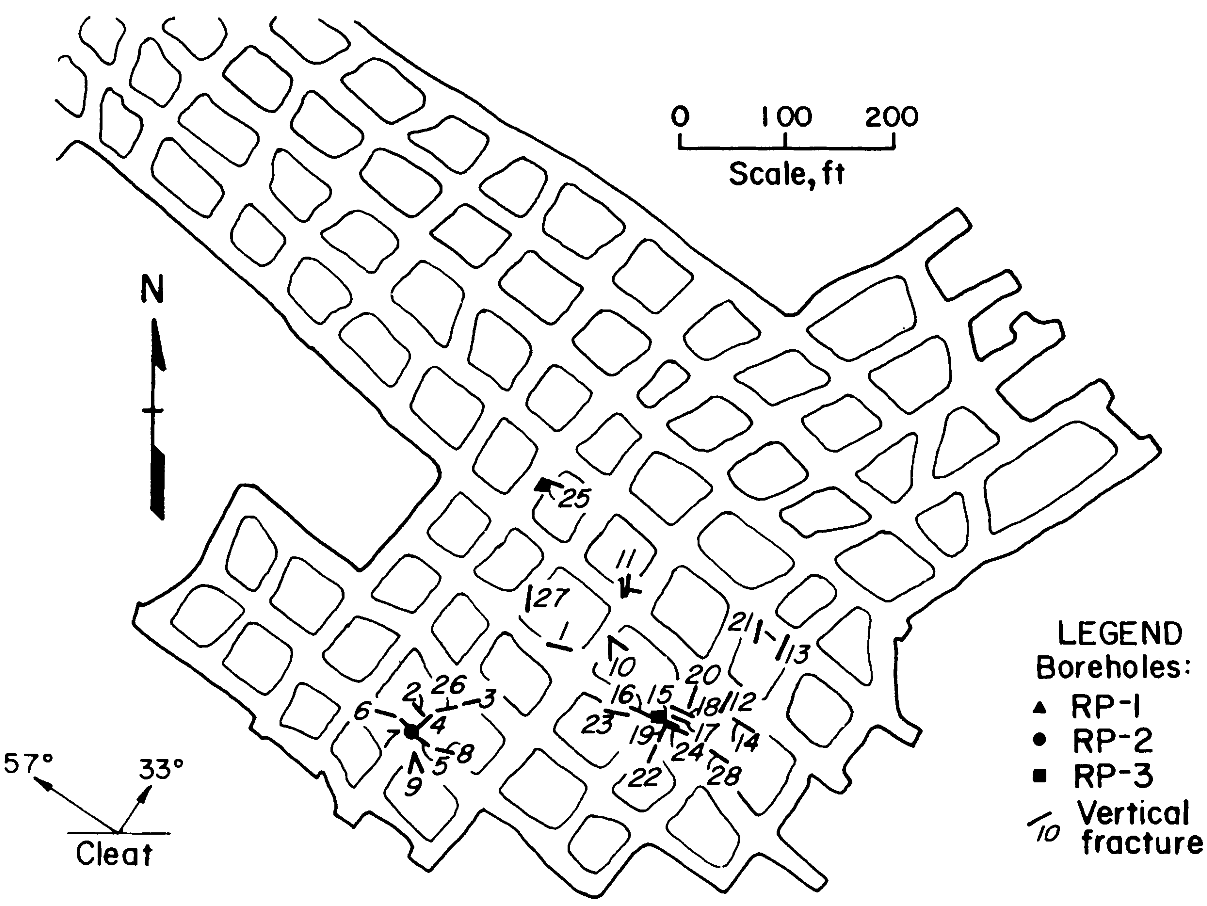

Figure 37.—Mine map, boreholes RP-1 through RP-3, with fracture orientations (*12*).

wide were present in the lower bench of coal below the shale parting (fig. 38). Two fractures contained sand that is assumed to have come from the sand placed at the bottom of the hole to protect the coalbed from cement invasion during the casing and cementing operation, since no sand was injected as part of the treatment.

Several of the vertical fractures extended through the shale parting and into the upper bench. Pink-paint-tagged grout that had been used to plug the hole for abandonment was found in the upper portion of fractures whose lower portion contained sand. All of the fractures were aligned parallel to the face cleat (N 76° W) and were coated with green paint. Fractures that contained only paint were visible using the ultraviolet light. They appeared to be no wider than the face cleat itself. The sand-filled fractures were approximately 1/16 in wide. The most prominent vertical fracture could be traced with the ultraviolet light laterally across a small patch of roof coal remaining around the borehole. The fracture in the roof coal extended laterally from the borehole approximately 6 in to the nearby rib and 19 in into the entry in the opposite direction. The fluids followed a stairstep path alternating along the face and butt cleat in the roof coal, and did not travel along a single face cleat for more than 1 or 2 in. A summary of the orientation and fracture observations is given in table 8.

No evidence of horizontal fracturing was found close to borehole RP-1, but traces of the green paint were found on the roof shale at several points in the entry. The inferred horizontal extent of the paint pigment is shown in figure 39.

The vertical fractures either terminated at the roof or before reaching the roof. No evidence of roof penetration by the stimulation was observed. A small roof fall did occur at an intersection approximately 25 ft southwest of the borehole several days after being mined. The roof fall was attributed to the presence of compactional slips in the black shale roof. Examinations of the area with the ultraviolet light failed to detect any paint on any surface associated with the fall or around the fall. Similar roof falls related to slips are common in this area of the mine.

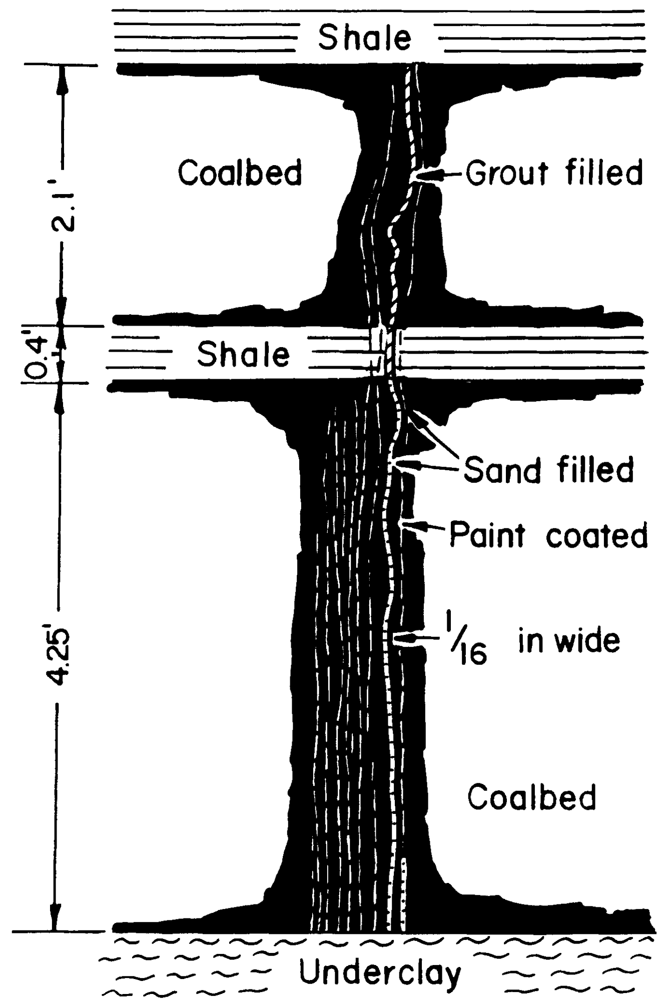

Figure 38.—Cross section of fractures at location 25 on the southeast rib near borehole RP-1. (Modified from Murrie (*12*))

Table 8.—Orientation and description of vertical fractures, boreholes RP-1 through RP-3 (*12*)

Location[1]	Number of fractures	Quadrant bearing	Fracture filling materials[2]	Location[1]	Number of fractures	Quadrant bearing	Fracture filling materials[2]
1	1	N 70° E	R, Y	14	1	N 60° W	O, Y
2	1	N 46° W	O, Y	15	1	N 73° W	O, Y, S, C
3	1	N 69° E	O, Y		1	N 66° W	O, Y, S, C
4	1	N 59° E	O, Y, S	16	1	N 62° W	O, Y, S
5	1	N 54° W	O, Y, S, C	17	1	N 66° W	R
6	4	N 69° W	O, Y, S	18	1	N 71° W	R
7	1	N 54° W	O, Y, S, C		3	N 66° W	R
8	1	N 73° W	O	19	1	N 24° E	R, Y
9	1	N 33° E	O, Y	20	1	N 19° E	R, Y
	1	N 34° W	O, Y	21	9	N 66° W	Y
10	1	N 70° E	O, Y	22	1	N 21° E	R
	1	N 26° E	O, Y	23	1	N 66° W	R
11	1	N 9° E	R, Y	24	1	N 71° W	R
	1	N 19° E	R, Y	25	9	N 76° W	G, S, C
	1	N 86° W	R, Y	26	1	N 59° E	O, Y, S
12	1	N 27° E	Y	27	2	N 22° E	R
13	1	N 27° E	Y	28	1	N 69° W	Y

[1]Shown on figure 37.
[2]Types of fracture-filling materials—R, red paint; O, orange paint; G, green paint; S, sand; C, cement grout.

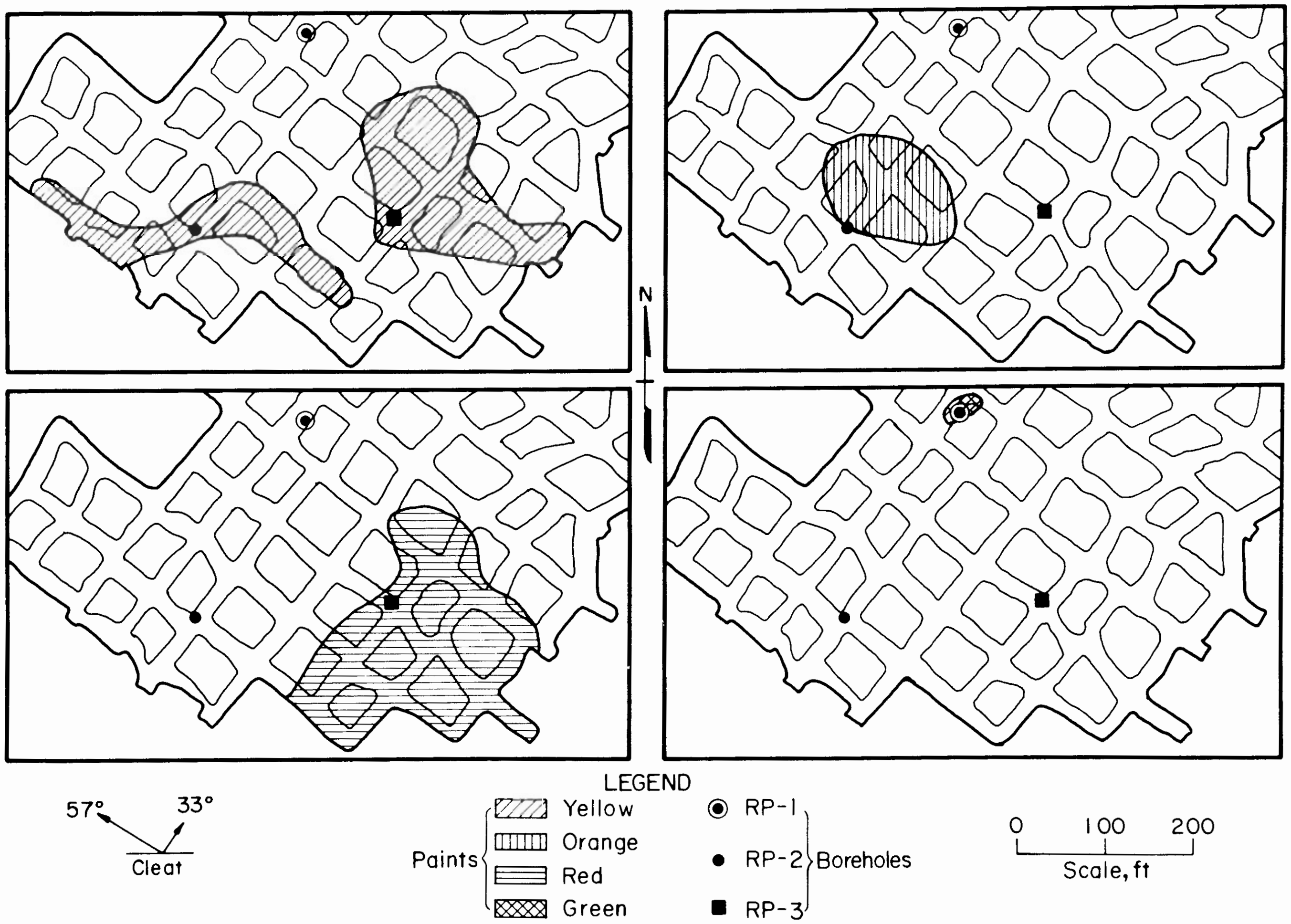

Figure 39.—Mine map, boreholes RP-1 through RP-3, with horizontal distribution of paint on roof (*12*).

LUCERNE NO. 6 MINE, BOREHOLE RP-2 (*12*)

Borehole Completion

Borehole RP-2 was drilled with air, 6 in. in diameter, to a depth of 660 ft, approximately 24 ft below the base of the target Upper Freeport Coalbed. The coalbed was 5.75 ft thick with a 7-in-thick shale parting near the top of the coal interval, and was located from 630.4 to 636.15 ft in the borehole. Prior to casing the borehole, sand was used to fill the hole to the top of the coalbed as an extra precaution against cement penetration of the coal interval. The borehole was cased with 4½-in-OD casing with a cement basket shoe on the bottom as the primary means of keeping cement from reaching the coalbed below the casing. The bottom of casing was set at 627 ft, 3.4 ft above the top of the coalbed. Debris falling on top of the sand pack during the running of the casing prevented placing the bottom of the casing closer to the desired top of the coalbed. The cement basket shoe and sand pack were drilled out to a depth of about 2 ft below the base of the coalbed in preparation for stimulation.

Treatment Implementation (January 27, 1982)

Prestimulation strata characterization tests on this borehole were limited to gamma ray and density wireline geophysical logs and laboratory mechanical property tests on general mine samples as described in the discussion of borehole RP-1. Prior to initiating the stimulation treatment, a jetting tool was positioned approximately 1.5 ft above the base of the coalbed and rotated to erode a horizontal slot in the coalbed below the shale parting. The stimulation treatment for borehole RP-2 was designed to consist of 30,000 gal of 75-pct-quality nitrogen-generated foam and 15,000 lb of 20/50-mesh sand proppant.

Breakdown pressures in borehole RP-2 were 1,170 lbf/in^2(ga) bottom hole and 945 lbf/in^2(ga) surface, using clear water. The continuous stimulation treatment record is shown in figure 40. Blue fluorescent paint was added to the foam pad. A summary of the paint colors, sand rates, and fluid volumes used in the treatment is given in table 7. Pump problems and time restrictions placed on the stimulation by the mine operator precluded pumping the scheduled 20,000-gal foam pad, which was reduced to 10,000 gal.

Treatment pressures declined from 1,210 to 1,105 lbf/in^2(ga) bottom hole and 1,150 to 1,060 lbf/in^2(ga) surface before problems with the fracturing pumps began. The initial sand concentration was 0.5 lb/gal of foam with orange fluorescent paint. After 13 min the sand concentration was increased to 1.0 lb/gal of foam with yellow fluorescent paint. The treatment pressure began a gradual increase almost immediately after increasing the sand

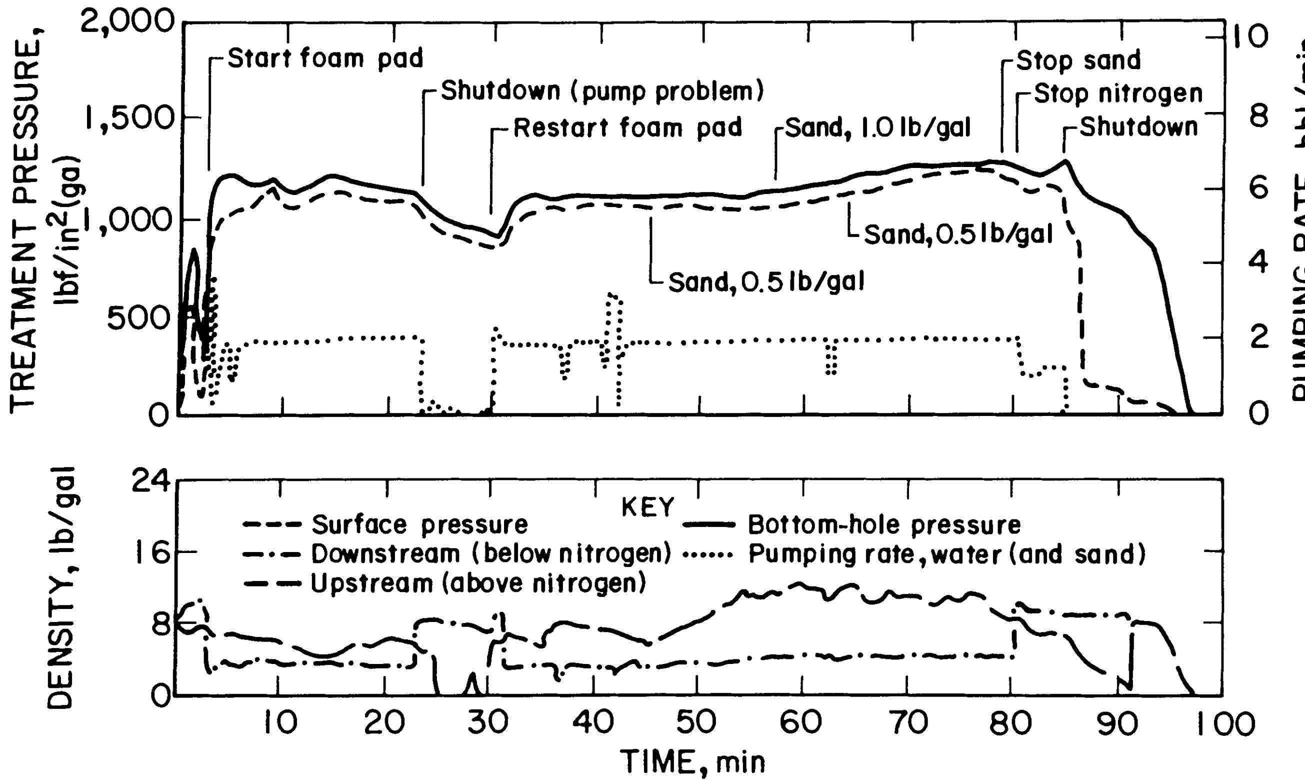

Figure 40.—Treatment record, borehole RP-2.

concentration, indicating either the inability of the induced fractures to accept, or inability of the foam to carry, the higher sand load. If the pressure had continued to increase unchecked, a point might have been reached where the foam could not have carried the suspended sand load, and a screenout or dropping of the sand in the wellbore would have occurred, prematurely terminating the treatment.

When it appeared that the bottom hole pressure would not stabilize or decline, the sand concentration was reduced to 0.5 lb/gal of foam for the remainder of the treatment. Maximum pressures during stage 2 were 1,300 lbf/in²(ga) bottom hole and 1,250 lbf/in²(ga) surface. The average surface treatment pressure was about 1,150 lbf/in²(ga). A total of 9,800 gal of foam and 7,000 lb of sand were injected into the coalbed during the second stage of the treatment.

Underground Observations

Borehole RP-2 was mined through on March 25, 1982, approximately 2 months after stimulation. The location of the borehole was approximately 25 ft from the expected location plotted from a deviation survey of the borehole. Numerous vertical fractures were observed surrounding the borehole. As mining approached the borehole from the northeast (subparallel to the butt cleat), several fractures in the butt cleat direction (N 31° E) were intercepted head on and traced to the borehole (**4**) (fig. 37). One of the butt cleat fractures (**26**) was sand filled to the point where it entered a pillar, 30 ft from the borehole. The trace of this fracture where it emerged on the opposite side of the pillar (**3**), 67 ft from the borehole, contained only paint. These fractures generally terminated at the floor and extended upward to the top of the shale parting. A horizontal component was also observed on the interface between the top of the shale parting and the upper coal bench. No extensions of the butt cleat fractures were observed beyond the borehole to the southwest.

Vertical fractures in the face cleat direction were observed as the borehole was mined through. One fracture (**7**) on the northwest rib (fig. 41) and one (**5**) to the southeast contained sand. The fracture on the northwest rib was closest to the borehole and was approximately ½ in wide and filled with sand proppant to the bottom of the parting. A second vertical fracture split off the main fracture approximately midway in the main bench of coal and rejoined near the base. Yellow and orange paint were found in the sand. The upper section of the fracture through the shale parting was filled with grout tagged with pink paint used to plug the hole for abandonment. The grout also extended a few inches horizontally along the interface between the shale parting and the upper bench of coal (fig. 41). Sand was found beyond the grout on the same horizontal plane in the rib for a maximum distance of 17 ft from the borehole to the northeast (fig 42). The vertical sand-filled portion of the fracture narrowed to approximately 1/16 to 1/8 in where it extended to the southeast rib (**5**). Grout from the plugging operation was again found in the vertical fracture through the shale parting. Sand was present for a short distance horizontally at the interface between the top of the shale parting and the upper coal bench. A summary of the vertical fracture observations is given in table 8.

The extent of paint on the horizontal interface between the top of the shale parting and the upper coal

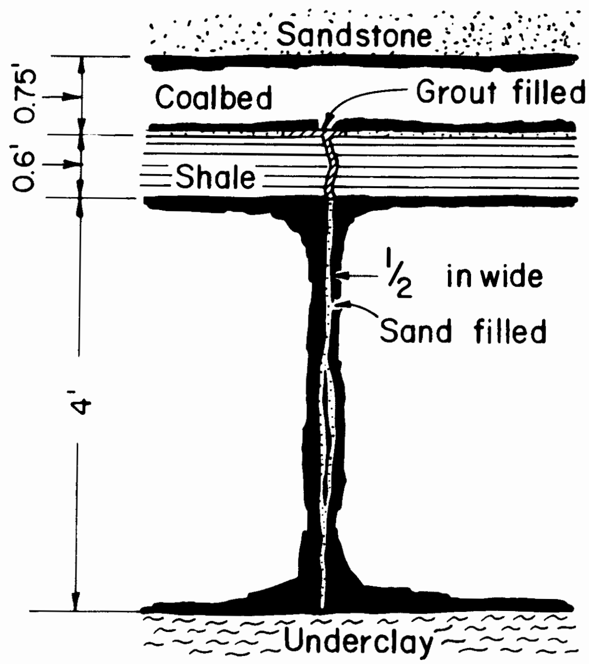

Figure 41.—Cross section of fractures at location 7 on the northwest rib near borehole RP-2. (Modified from Murrie (*12*))

bench (fig. 42) indicated a wide distribution of fluids on that surface. The orange paint was found a maximum of 265 ft from the wellbore. The yellow paint from RP-2 and the nearby RP-3 apparently overlapped, but the maximum horizontal extent seems to have been about 200 ft. Yellow and orange paint were also found on the horizontal plane between the top of the coal and the roof. The horizontal extent of paint on this plane, as shown in figure 39, was substantially less than on top of the shale parting. The pattern of the yellow paint on the roof, with two lobes elongated parallel to the face cleat and a connecting lobe parallel to the butt cleat suggests some influence of the vertical coal cleat on the horizontal distribution of the stimulation fluids. No sand was found along the interface between the roof and coalbed. Most of the sand proppant injected into this borehole was contained in only a few vertical fractures. There was no evidence of roof penetration by the stimulation fluids.

LUCERNE NO. 6 MINE, BOREHOLE RP-3 (*12*)

Borehole Completion

Borehole RP-3 was drilled with air, 6-in. in diameter, to a depth of 675 ft, approximately 35 ft below the base of the target Upper Freeport Coalbed. The coalbed was 5.5 ft thick with a 5-in-thick shale parting near the top of the

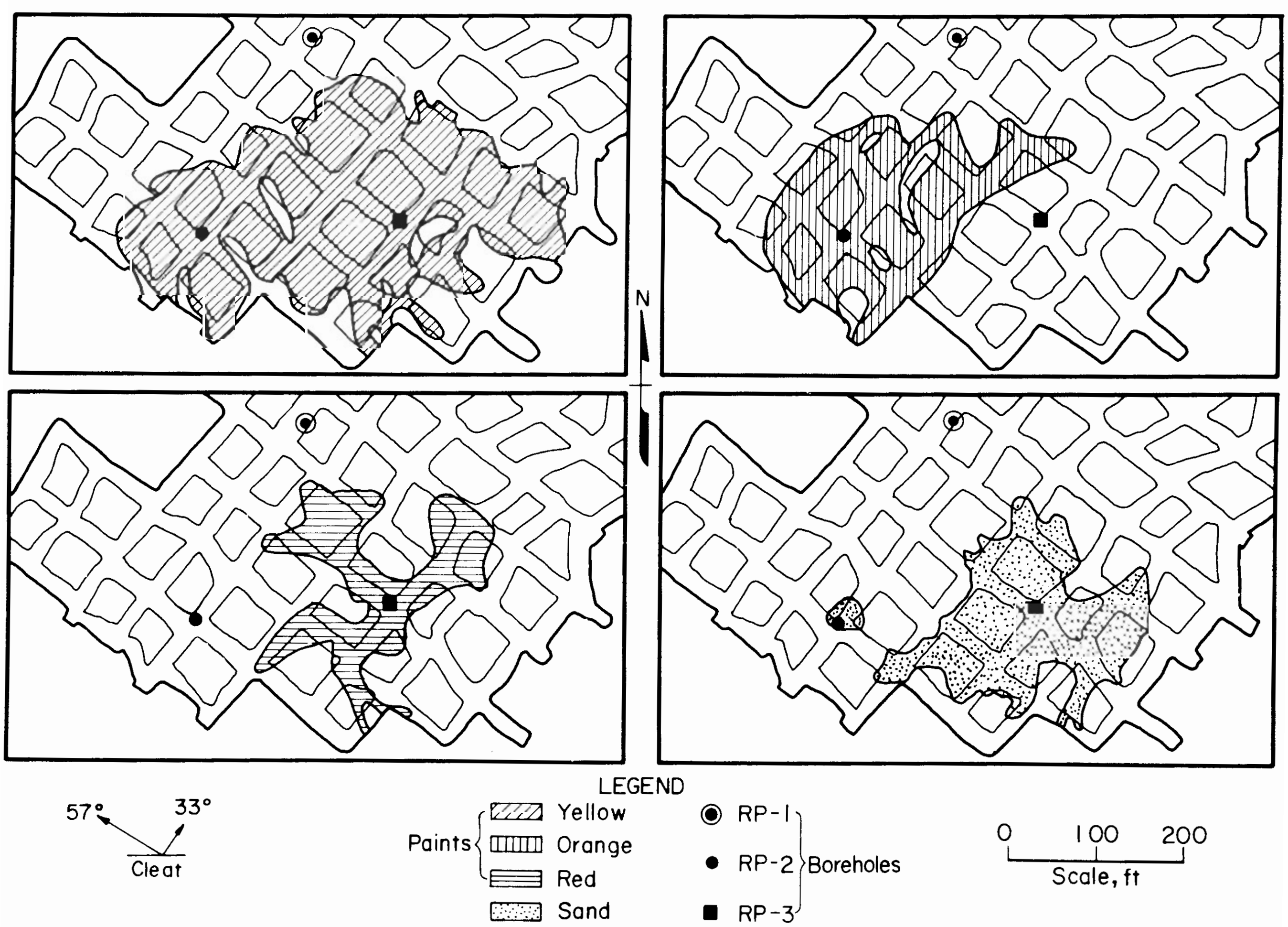

Figure 42.—Mine map, boreholes RP-1 through RP-3, with horizontal distribution of paint and sand on top of shale parting (*12*).

coal interval and was located between 634.6 and 640.1 ft in the borehole. Prior to casing the borehole, sand was used to fill the hole to the top of the coalbed as an extra precaution against cement penetrating the coal interval. The borehole was cased with 4½-in-OD casing with a cement basket shoe on the bottom as the primary means of keeping cement from reaching the coalbed below the casing. The bottom of casing was set at 632 ft, 2.6 ft above the top of the coalbed. As was the experience at the other two boreholes at this mine site, debris on top of the sand pack prevented placing the bottom of casing closer to the desired top of the coalbed. The cement basket shoe and sand pack were drilled out to a depth of about 2 ft below the base of the coalbed in preparation for stimulation.

Treatment Implementation (January 30, 1982)

Prestimulation strata characterization tests on this borehole were limited to natural gamma ray and density wireline geophysical logs and laboratory mechanical property tests on general mine samples as described in the discussion of borehole RP-1. Prior to initiating the stimulation treatment, a jetting tool was positioned approximately 1.5 ft above the base of the coalbed and rotated to erode a horizontal slot in the coalbed below the shale parting. The stimulation treatment for borehole RP-3 was designed to consist of 30,000 gal of 75-pct-quality nitrogen-generated foam and 15,000 lb of the 20/50-mesh sand proppant.

The stimulation of borehole RP-3 began with a small volume of clear water to break down the coalbed. The continuous stimulation treatment record is shown in figure 43. Breakdown pressures were 1,320 lbf/in²(ga) bottom hole and 1,080 lbf/in²(ga) surface. A 20,000-gal foam pad with red fluorescent paint was injected at a rate of 6 bbl/min. At the end of the pad, sand proppant was added to the treatment in concentrations that were gradually increased from 0.5 to 1.5 lb/gal of foam in increments of 0.5 lb/gal. At each increase in sand concentration a different paint color was introduced as shown in table 7. A total of 11,500 lb of sand was injected with 10,200 gal of foam during stage 2. Pressures declined from 1,365 lbf/in²(ga) bottom hole and 1,110 lbf/in²(ga) surface at the beginning of the foam pad to 815 lbf/in²(ga) bottom hole and 750 lbf/in²(ga) surface at the end of the treatment with no apparent increase in pressures as sand was introduced or its concentration increased. Average surface treatment pressure was about 850 lbf/in²(ga).

During the latter portion of the stimulation treatment of borehole RP-3, communication was observed with borehole RP-2, where small amounts of foam were detected bubbling from the casing. The two boreholes are approximately 225 ft apart and on a line that is oriented 25° from the face cleat direction. It is possible that the decrease in treatment pressure resulted in part from the fractures created in the stimulation of borehole RP-3 entering the area previously affected by the treatment of borehole RP-2.

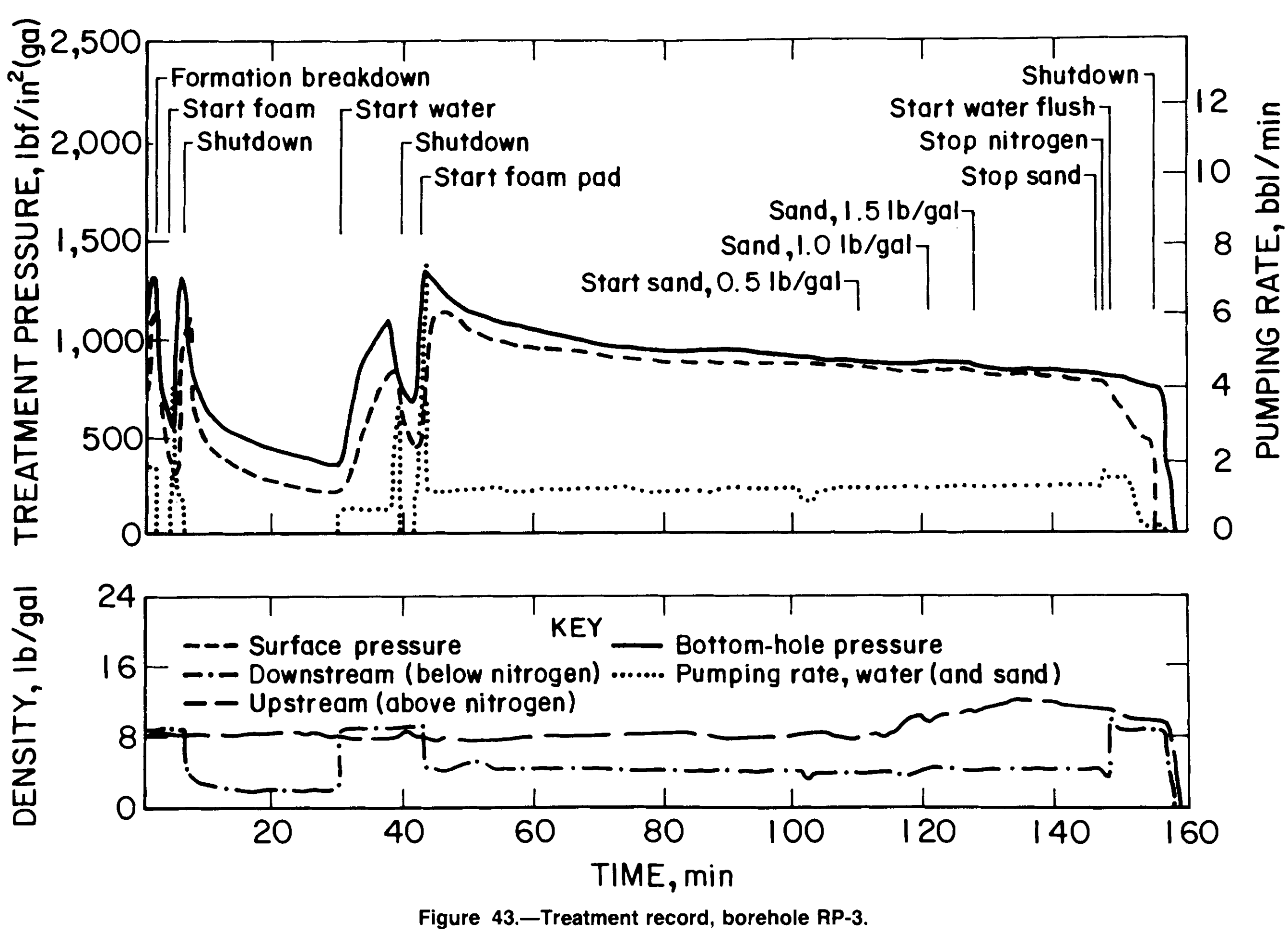

Figure 43.—Treatment record, borehole RP-3.

Underground Observations

Borehole RP-3 was mined through on May 18, 1982, approximately 4 months after stimulation. The location of the borehole was approximately 25 ft from the expected location plotted from a deviation survey of the borehole. The greatest number of vertical fractures at the Lucerne No. 6 Mine site were found associated with borehole RP-3 (fig. 37), which also had the largest stimulation treatment. Most of the vertical fractures seen near the wellbore were parallel to the face cleat. One butt cleat fracture was traced from the borehole (**19**) to the rib (**22**) of the pillar south of the hole and several others (**12-13, 20-21**) were observed at greater distances away from the borehole. The only sand-filled fractures (**15-16**) were in the face cleat direction and were oriented in a direction that would intercept the borehole. Representative cross sections of the northwest (**16**) and southeast (**15**) wings of this dominant fracture are shown in figure 44. The other vertical fractures associated with this borehole contained various combinations of red, yellow, and orange fluorescent paint on cleat surfaces in the lower bench of coal.

The vertical fracture on the northwest rib (**16**) was filled with sand, had a maximum width of approximately 1 in, and tapered to the width of a cleat at the base. This sand-filled fracture extended upward through the shale parting and became horizontal on top of the parting. Orange and yellow paint were found in the fracture (**16**) nearest the hole in the northwest direction and only red was found further out (**23**) in this direction. The sand-filled wing of this major fracture (**15**) on the southeast rib (fig. 44) was slightly more complex than that on the northwest rib. Two nearly parallel vertical sand- and grout-filled (from the plugging operation) fractures were present. The sand filling extended from the floor to about halfway up the main coal bench, and the grout filled the remainder of each fracture up to its maximum vertical extent. Maximum width was 3/8 in. The shorter vertical fracture terminated approximately 2 in below the parting. The other fracture terminated at the bottom of the shale parting, but a horizontal sand-filled fracture split off from it 2 in below the parting. This split intercepted the parting at a shallow angle and then cut through it at approximately 45° and became horizontal on top of the parting. Orange and yellow fluorescent paint were found in the fractures (**15**) closest to the borehole in this direction, red only slightly further away (**24**), and finally yellow only at the furthest extent of this fracture on the next rib (**28**). A summary of the vertical fracture observations is given in table 8.

Sand on the interface between the top of the shale parting and the upper bench of coal was found a maximum of 200 ft from the borehole (fig. 42). Yellow was the most widespread paint on top of the binder, extending a maximum of 200 ft, however, there was an apparent overlap with the yellow paint injected in borehole RP-2. Red paint was found over a wide area, and was distributed in a pattern that consisted of several lobes elongated parallel to the face and butt cleat directions. This again suggests some control of the horizontal fluid placement by the cleat system in the coalbed. Very little orange paint was found on the top of the shale parting, perhaps because it was masked by the red and yellow paints. No blue paint was seen in any of the fractures at the Lucerne No. 6 Mine, probably because of the inability to distinguish it from the glow of the ultraviolet light being used and because of large areas of blue fluorescent hydraulic fluid (from leaking hoses on mining equipment) on the ribs. No sand was found on the interface between the roof and the top of the coalbed, but red and yellow fluorescent paint were mapped as shown in figure 39.

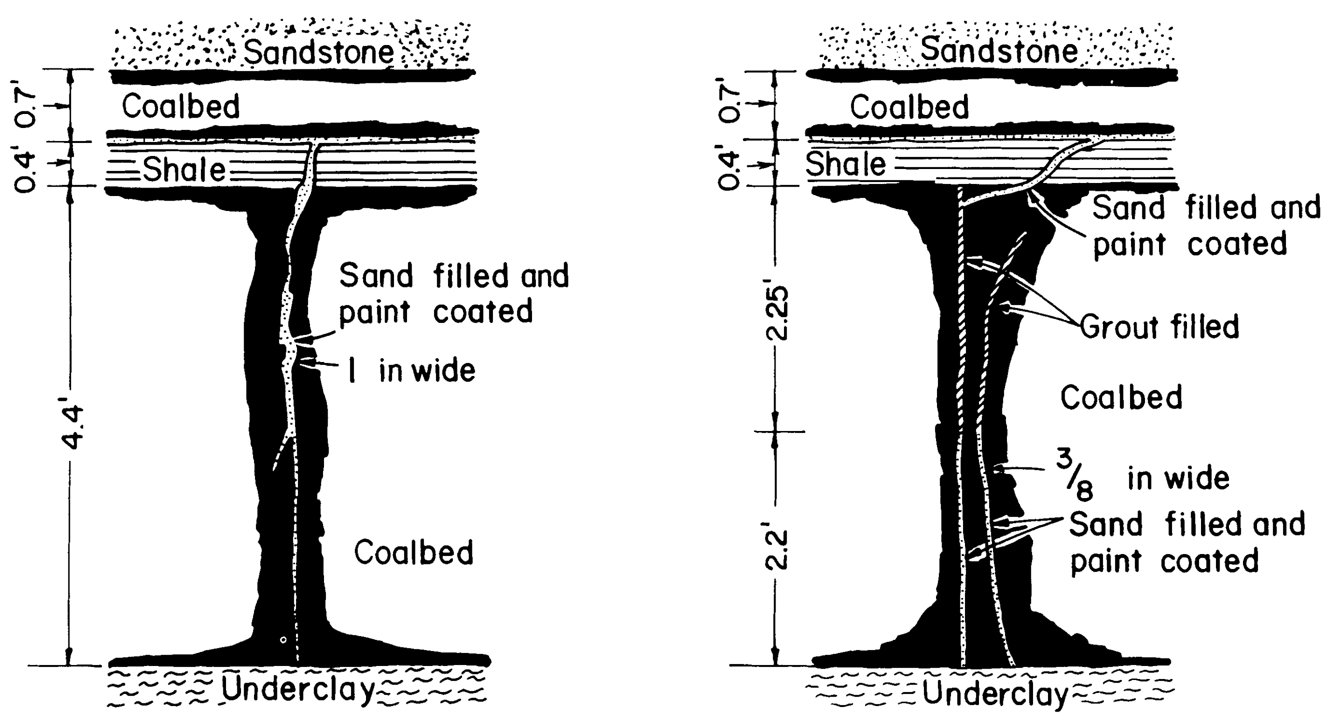

Figure 44.—Cross section of fractures at location 15 on southeast rib (right) and location 16 on northwest rib (left) near borehole RP-3. (Modified from Murrie (*12*))

LOWER KITTANNING COALBED, WEST VIRGINIA

KITT NO. 1 MINE, BOREHOLE KE-2 (*12*)

Borehole Completion

Borehole KE-2 was drilled with air, 7 in. in diameter, to a depth of 685 ft, approximately 20 ft below the base of the target Lower Kittanning Coalbed. The coalbed was 5.2 ft thick, and was located at a depth of 660 to 665.2 ft in the borehole. Prior to casing the borehole, sand was used to fill the hole to the top of the coalbed as an extra precaution against cement penetration of the coal interval. The borehole was cased with 4½-in-OD casing with a cement basket shoe on the bottom as the primary means of keeping cement from reaching the coalbed below the casing. The bottom of casing was set at 659.5 ft, 0.5 ft above the top of the coalbed.

Treatment Implementation (March 19, 1982)

Prestimulation strata characterization tests on this borehole included caliper, gamma ray, and density wireline geophysical logs. A series of mechanical property tests to measure triaxial compressive strength, Young's modulus, and residual friction angles and coefficients were conducted on coal and surrounding rock samples collected at the mine. Analysis of the test results indicated that the roof shale tested was abnormally weak and soft for the rock type (*25*). This weak roof material is probably at least partially responsible for the severe roof control problems generally experienced at the mine. Extensive mapping of existing geologic conditions was conducted at the mine to aid in interpreting the effect of the treatment on the coalbed and surrounding strata. The details of the geologic characterization can be found in reference 12.

Borehole KE-2 was stimulated with 75-pct-quality nitrogen-generated foam and sand proppant. The continuous stimulation treatment record is shown in figure 45. The coalbed was broken down using a small volume of water. Pressures were 1,050 lbf/in^2(ga) bottom hole and 1,000 lbf/in^2(ga) surface. The 20,000-gal foam pad with red fluorescent paint was injected into the coalbed at a rate of 8 bbl/min. Treatment pressures gradually increased from 1,050 to 1,130 lbf/in^2(ga) bottom hole and 1,000 to 1,090 lbf/in^2(ga) surface at the end of the foam pad. Stage 2 began with the introduction of sand proppant at a concentration of 1.5 lb/gal along with the yellow fluorescent paint. Treatment pressure increased to 1,340 lbf/in^2(ga) bottom hole and 1,290 lbf/in^2(ga) surface, leveled off, then rapidly rose to 2,300 lbf/in^2(ga) bottom hole and 2,000 lbf/in^2(ga) surface. The rise in treatment pressure was so rapid that the sand injection could not be stopped quickly enough to prevent a screenout and

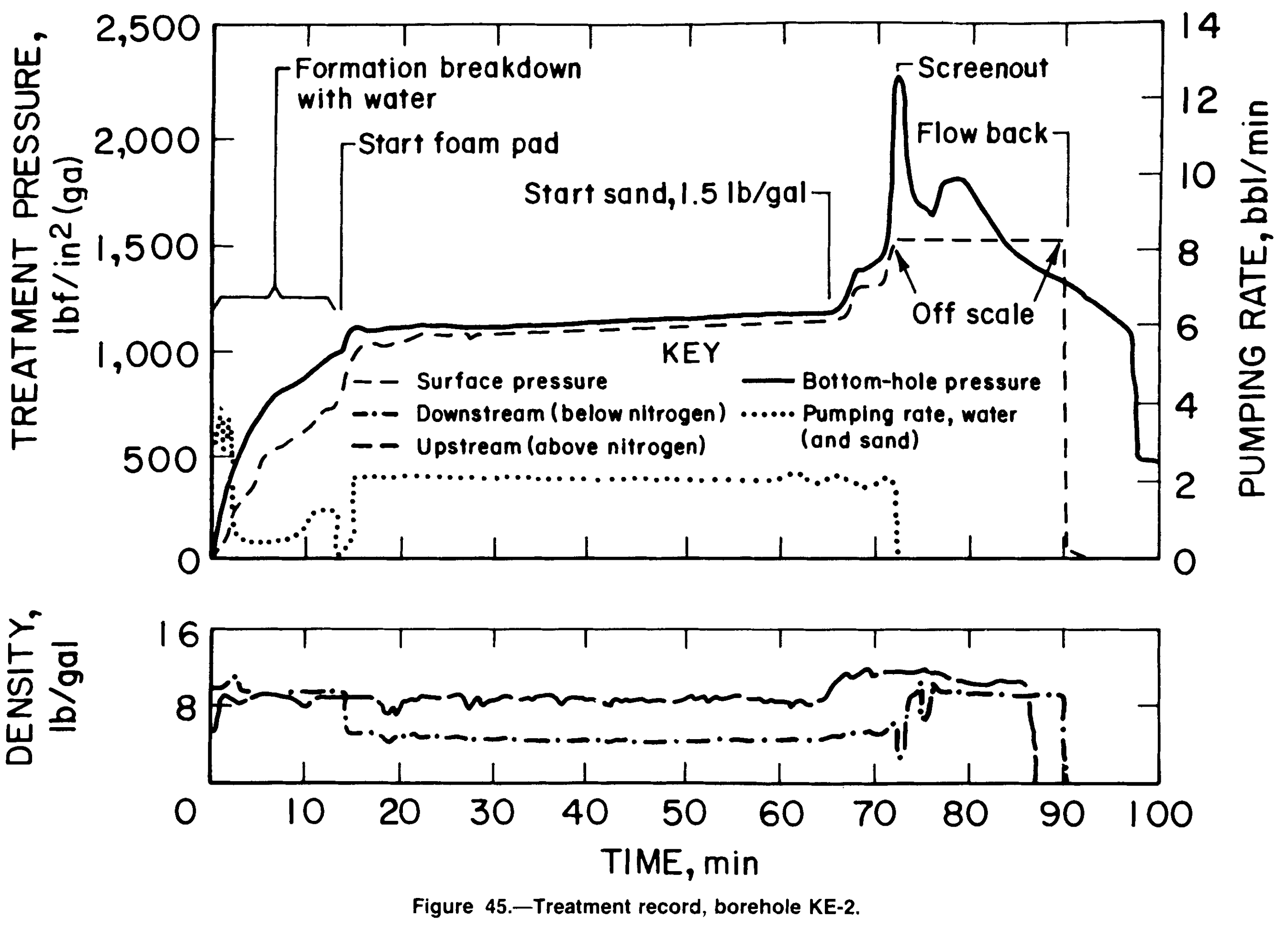

Figure 45.—Treatment record, borehole KE-2.

termination of the treatment. Only 3,500 gal of the scheduled 7,000 gal of foam and 3,300 lb of the scheduled 10,000 lb of sand proppant were injected during stage 2. A review of the treatment record after the job indicated that the calculated foam quality was 54 to 60 pct, not the required 75-pct quality necessary to carry the sand concentration specified, thereby contributing to the screenout.

Underground Observations

A paint-coated fracture from borehole KE-2 was intercepted on November 18, 1982, approximately 8 months after stimulation. The stimulation treatment from borehole KE-2 was intercepted at a point approximately 85 ft from the borehole (fig. 46). A single vertical face cleat plane with red paint was observed. No sand proppant was found. The paint terminated at the floor and disappeared before reaching the roof. A small area of red paint was found on the roof shale approximately 38 ft from the vertical fracture, but none was observed on the sandstone roof exposure closer to the vertical fracture. Poor roof conditions were found in the transition zone between the shale and sandstone roof; however, similar roof conditions are common throughout the Kitt No. 1 Mine. Because of the poor roof conditions generally associated with this type of transition zone, several longwall panels were shortened to avoid mining through the zone and under the sandstone roof rock. Because of the change in the mining plans, the underground characterization of the stimulation was limited. There was no evidence of any penetration of the roof by the stimulation treatment nor any evidence of any influence on the roof conditions.

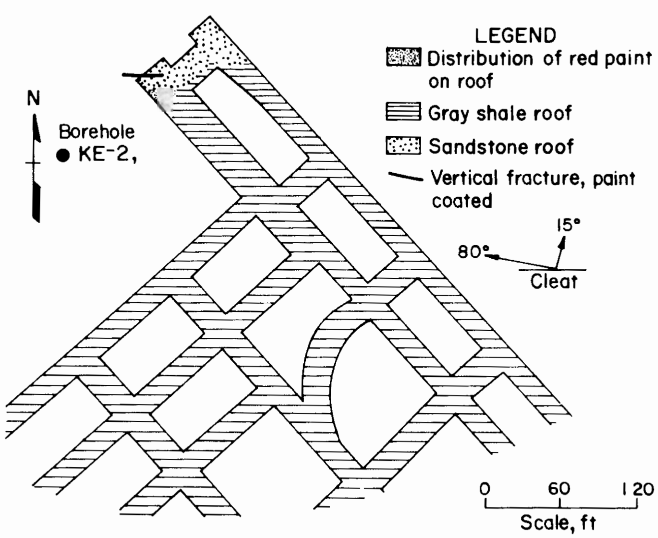

Figure 46.—Mine map, borehole KE-2, with fracture orientation. (Modified from Murrie (*12*))

KITT NO. 1 MINE, BOREHOLE DGBH-5

Borehole Completion

Borehole DGBH-5 was drilled with air, 10 in. in diameter, to a depth of 653.5 ft, approximately 11 ft below the base of the target Lower Kittanning Coalbed. The coalbed was 5.5 ft thick, and was located at a depth of 637.3 to 642.8 ft in the borehole. Prior to casing the borehole, sand was used to fill the hole to the top of the coalbed as an extra precaution against cement penetration of the coal interval. The borehole was cased with 7-in-OD casing with a cement basket shoe on the bottom as the primary means of keeping cement from reaching the coalbed below the casing. The bottom of casing was set just above the top of the Lower Kittanning Coalbed.

Treatment Implementation (April 2, 1982)

Prestimulation strata characterization tests on this borehole included caliper, gamma ray, and density wireline geophysical logs. The treatment for borehole DGBH-5 consisted of two stages, the first being a 40,320-gal foam pad and the second 10,080 gal of foam with 11,800 lb of 20/50-mesh sand proppant. The treatment was conducted through the annulus between the casing and the tubing used to obtain bottom hole pressure. The coalbed was first broken down with a small volume of clear water at pressures of 860 lbf/in^2(ga) bottom hole and 1,210 lbf/in^2(ga) surface. A continuous stimulation record for the treatment is shown in figure 47. Treatment pressures gradually declined to 490 lbf/in^2(ga) bottom and 1,140 lbf/in^2(ga) surface at injection rates of 8 bbl/min. Average surface treatment pressure was about 950 lbf/in^2(ga). Sand proppant was introduced at the end of the foam pad in concentrations that were gradually increased from 0.25 to 1.5 lb/gal in increments of 0.25 lb/gal. Because of mechanical problems with the methane engines used to power the pumping unit on this borehole, continuous water and gas production were never achieved.

Underground Observations

Sand-filled fractures from borehole DGBH-5 were intercepted by mining in August 1984, approximately 2⅓ yr after stimulation. A sand-filled vertical fracture was intercepted in the entry closest to the borehole (fig. 48). The fracture was approximately ½ in wide on the east rib closest to the borehole. The fracture paralleled the face cleat, but followed a sinuous path as shown in figure 49. The fracture extended from the floor to the roof, but did not penetrate the roof. The mine operator reported a flow of water and gas from the fracture for some period of time after interception. The flow of water and gas was probably due to the inability to produce the borehole prior to interception.

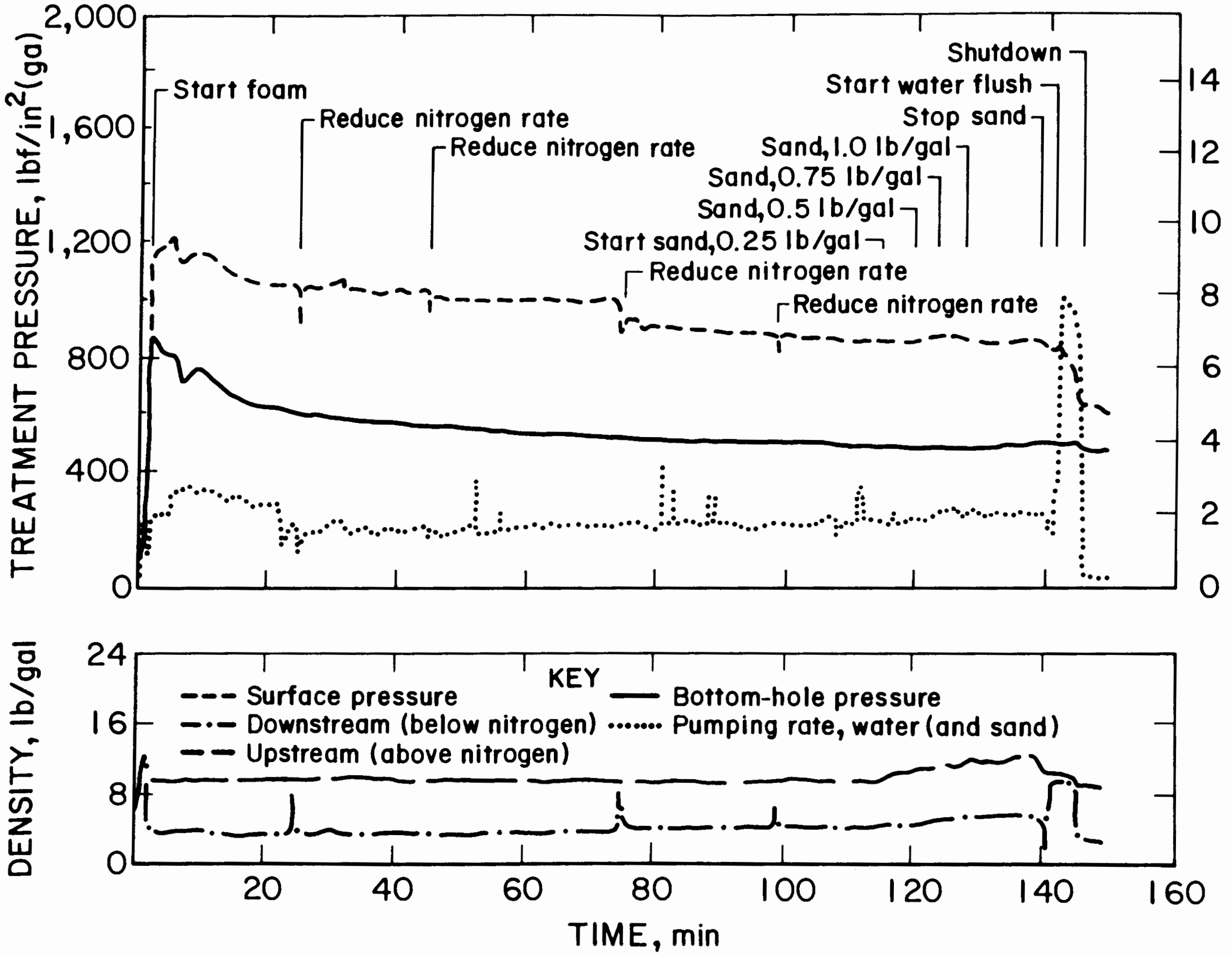

Figure 47.—Treatment record, borehole DGBH-5.

The fracture became horizontal at the interface between the top of the coalbed and the roof where it was generally only a few sand grains thick. Sand could be traced horizontally along the east rib a maximum of 29 ft from the vertical fracture.

The vertical fracture was also found on the opposite side of the entry on the west rib. The fracture was 3/8 in wide and extended from floor to roof (fig. 49). The fracture was parallel to the face cleat along a sinuous path similar to that on the east rib. There were several thin (several sand grains wide) vertical fractures in the lower section of the coalbed parallel to the primary fracture. The fracture became horizontal at the interface between the top of the coalbed and the roof, and sand could be traced a maximum of 51 ft from the position of the vertical fracture on the west rib. The distance from the presumed location of the borehole to the vertical trace on the west rib was 72 ft and the maximum distance that sand on the horizontal surface was found from the presumed location of the borehole was 105 ft. No penetration of the roof was observed at the west rib or across the roof of the entry between the two vertical exposures. A thorough inspection of the coalbed on both sides of the entry on the opposite side of the west pillar failed to reveal any sand-filled vertical or horizontal extension of the fracture.

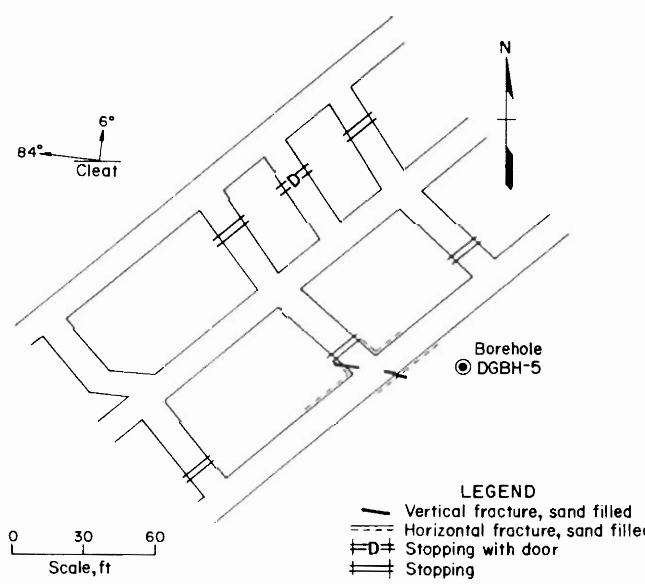

Figure 48.—Mine map, borehole DGBH-5, with fracture orientations.

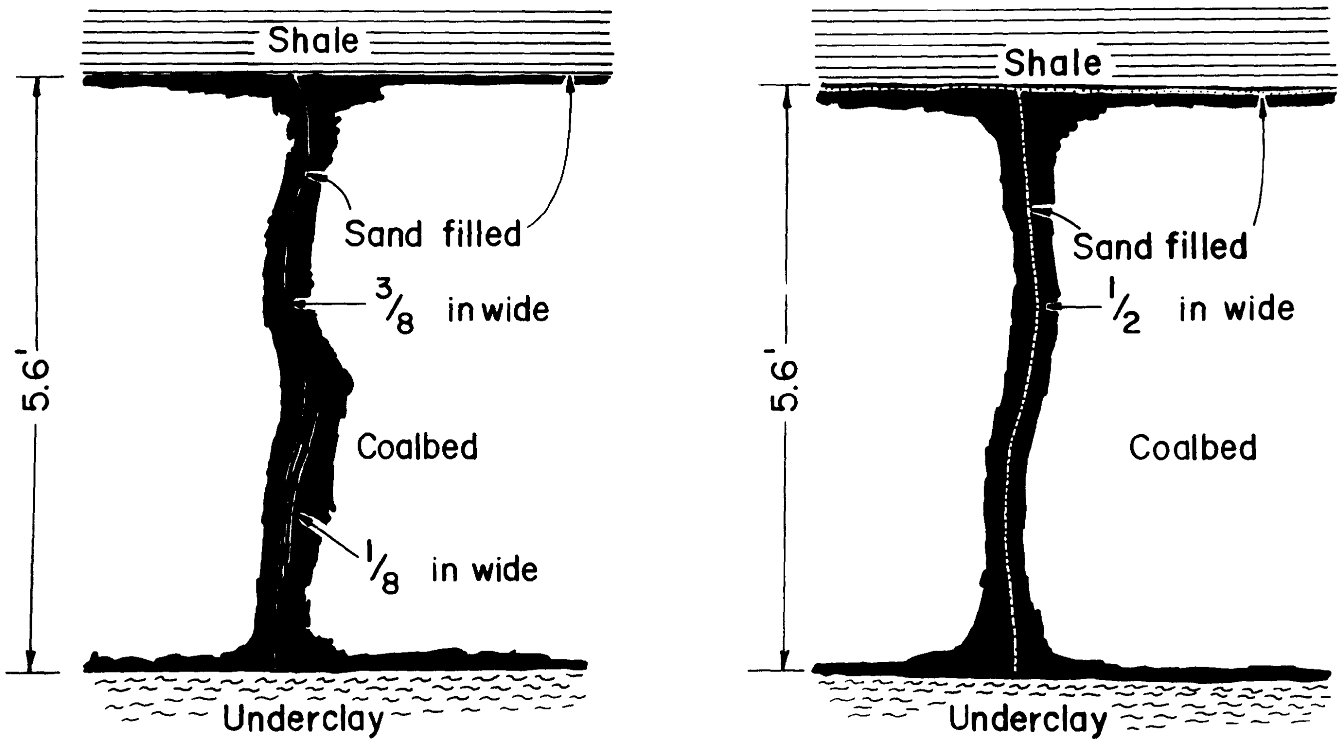

Figure 49.—Cross section of fractures on east (right) and west (left) ribs near borehole DGBH-5.

ILLINOIS NO. 6 COALBED, ILLINOIS

INLAND STEEL MINE, BOREHOLE 1-NE (8)

Borehole Completion

Borehole 1-NE was drilled 9 in. in diameter to a depth of 743 ft. The hole was cased to within a few feet of the top of the coalbed with 7-in-OD casing. The target Illinois No. 6 Coalbed was 9 ft thick and was located from approximately 729 to 738 ft in the borehole. The coalbed was overlain by a thick sandy shale.

Treatment Implementation (February 19, 1974)

Borehole 1-NE was treated through 2⅜-in-diameter tubing with a packer set in the casing at a depth of 720 ft, and the open end of the tubing extending to the middle of the coalbed at a depth of 733 ft. The treatment design to be implemented was to use gelled water (20 lb of guar gum per 1,000 gal of water) and sand to create two fracture wings, each 431 ft long, of which 305 ft would be propped by sand, 6.9 ft high and 0.2 in wide. A 2,000-gal gelled water pad was first injected into the coalbed to control leakoff. The continuous stimulation treatment record is shown on figure 50. Formation break was reported at 1,050 lbf/in^2(ga) surface. A pumping rate of 10 bbl/min was maintained throughout the treatment. Following the pad, an additional 10,000 gal of gelled water and 6,400 lb of 10/20-mesh sand was injected into the coalbed according to the schedule shown in table 9. The average injection pressure was 850 lbf/in^2(ga) surface. Gas flows during the short production life of the borehole reached only 4,300 ft^3/d, due in part to the low gas content of the coalbed.

Underground Observations

Fractures from the treatment were intercepted by mining in May 1974, approximately 3 months after stimulation. A single sand-filled vertical fracture was observed in four entries northeast of the presumed location of the borehole (fig. 51). The fracture extended from the roof to a hard shale parting approximately 2 ft from the bottom of the 9-ft-thick coalbed. The width of the fracture ranged from ⅛ to ⅜ in, averaging approximately ¼ in. A small amount of water drained from the fracture at the time of the mine-through. The sand-filled fracture could be traced across several entries in the 1 ft of roof coal generally left to protect the overlying shale from deterioration. The fracture in the roof coal was essentially the same width as the vertical exposures on the rib.

The orientation of the vertical fracture (N 76° E) did not coincide with either the face (N 34° W) or butt (N 45° E) cleat, but was closest to the butt cleat orientation (fig. 51). It is possible that the induced fracture orientation was influenced by the horizontal stress field in the area. The major horizontal stress axis in south-central Illinois has generally been reported (*26-27*) to be east to east-northeast, which would correspond quite well to the N 76° E fracture orientation. The reported fracture orientation could also be the result of unobserved stairstepping along face and butt cleat, which could give an apparent orientation for the fracture(s) oblique to the cleat orientation.

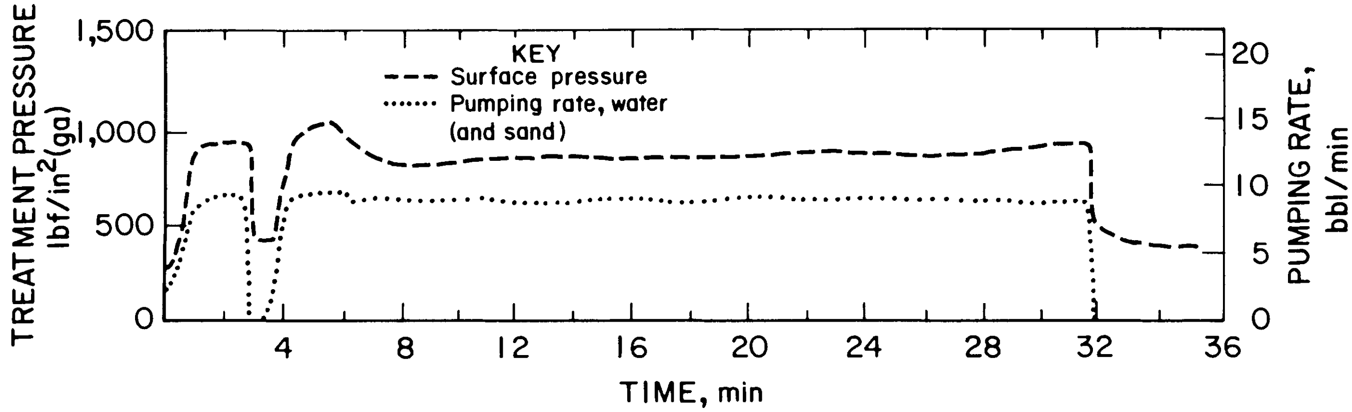

Figure 50.—Treatment record, borehole 1-NE. (Modified from Elder (*8*))

Table 9.—Summary of treatment chronology, borehole 1-NE (*8*)

Fluid volume, gal	*Sand rate, lb/gal*
2,000 (pad)	NAp
3,000	0.25
2,000	.50
1,800	.75
3,200	1

NAp Not applicable.

At its maximum lateral extent, the vertical fracture was observed 416 ft from the presumed location of the borehole. This is the greatest length observed to date for a sand-filled vertical fracture wing. There was essentially no penetration of the roof rock except at one point where Elder (*8*) reported "there was some evidence of fluid and sand intruding a few inches into a rock joint that crossed the induced fracture." No adverse mining conditions were reported as a result of the stimulation treatment, and even at a follow-up visit 2.5 yr after the stimulation there was still no deterioration. No horizontal fracture component was noted at this mine site.

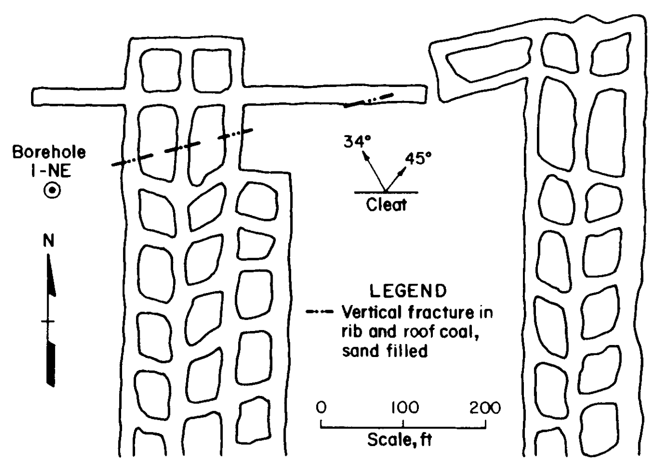

Figure 51.—Mine map, borehole 1-NE, with fracture orientations. (Modified from Elder (*8*))

JAWBONE COALBED, VIRGINIA

McCLURE NO. 1 MINE, BOREHOLE DG-1A (*9*)

Borehole Completion

Borehole DG-1A was drilled to a depth of approximately 455 ft. The hole was cased with 4½-in-OD casing to within about 2 ft of the top of the target Jawbone Coalbed. A packer shoe on the bottom of casing was used to keep cement from reaching the coalbed. The coalbed was 5 ft thick and was located from 425 to 430 ft in the borehole.

Treatment Implementation (July 29, 1978)

The borehole was treated down the casing with a packer installed at the surface. A continuous treatment record is not available for this borehole. The treatment was initiated with a 4,200-gal water pad. A formation break was reported at 1,000 lbf/in²(ga) surface. The primary treatment consisted of 35,300 gal of 75-pct-quality nitrogen-generated foam and 28,000 lb of 20/40-mesh sand proppant. The average pumping rate was 16 bbl/min. During a continuous production period over the first half of 1979, the borehole reached a maximum gas production rate of 45,000 ft³/d, then gradually declined to slightly less than 30,000 ft³/d. A detailed production history of the borehole can be found in the paper by Lambert (*9*). Chronic mechanical problems with the methane engine used to power the water pumping unit severely limited the production potential of the borehole.

Underground Observations

Borehole DG-1A was mined through on May 12, 1980, approximately 2 yr after stimulation. Both vertical and horizontal sand-filled fractures were observed, with the horizontal fractures predominating at the shallow depth of the coalbed. Vertical sand-filled fractures were found a maximum of 20 ft from the borehole and were oriented parallel to the face cleat. The vertical fractures were completely contained in the coalbed, and ranged from 5/8 in to a hairline in width. No evidence of roof penetration was observed. The horizontal fractures were generally observed approximately 2 to 5½ in below the top of the coalbed and ranged in thickness from 3/8 in to a hairline. The sand-filled horizontal fractures were observed over a large, generally elliptical, area around the borehole. The sand-filled horizontal fractures were observed a maximum of about 250 ft from the borehole.

ROCK CANYON COALBED, UTAH

SOLDIER CANYON MINE, BOREHOLE SC-1

Borehole Completion (*12*)

Borehole SC-1 was drilled 6 in. in diameter to a depth of 740 ft, approximately 42 ft below the base of the target Rock Canyon Coalbed. The borehole was cased with 4½-in-OD casing to the top of the coalbed. A cement basket shoe on the bottom of casing was used in addition to filling the hole with sand to the top of the coalbed to keep the cement from reaching the coalbed. The Rock Canyon Coalbed was 13.8 ft thick with 1.7 ft of shale partings in the upper 3.2 ft of the coalbed. The coalbed was located at a depth of 684 to 697.8 ft in the borehole.

Treatment Implementation (August 5, 1982) (*12*)

Prestimulation strata characterization included gamma ray, density, and caliper wireline geophysical logs. A jetting tool was positioned about 7 ft above the base of the coalbed and rotated to cut a horizontal slot. Coal particles in the fluid returns indicated that the tool had been placed in the coal interval. The stimulation treatment utilized 75-pct-quality nitrogen-generated foam, sand proppant, and green fluorescent paint. A 30,000-gal foam pad was injected first to control leakoff, followed by 20,000 gal of foam containing 15,000 lb of 20/40-mesh sand proppant. There was some evidence that the foam quality was lower than the specified 75 pct, therefore the actual foam volumes may be significantly less than reported by the service company. Foam treatment rates were maintained at approximately 16 bbl/min. Surface pressures during the injection of the foam pad quickly reached 1,000 lbf/in²(ga) then gradually increased to about 1,250 lbf/in²(ga). No obvious formation break was observed. The surface treatment pressure during sand injection reached a maximum of 1,500 lbf/in²(ga). The average surface treatment pressure was about 1,350 lbf/in²(ga). The continuous treatment record for this stimulation is shown in figure 52. The borehole was not completed for production since the project goals were to only stimulate and evaluate the effect of the stimulation treatment on the coalbed and surrounding strata.

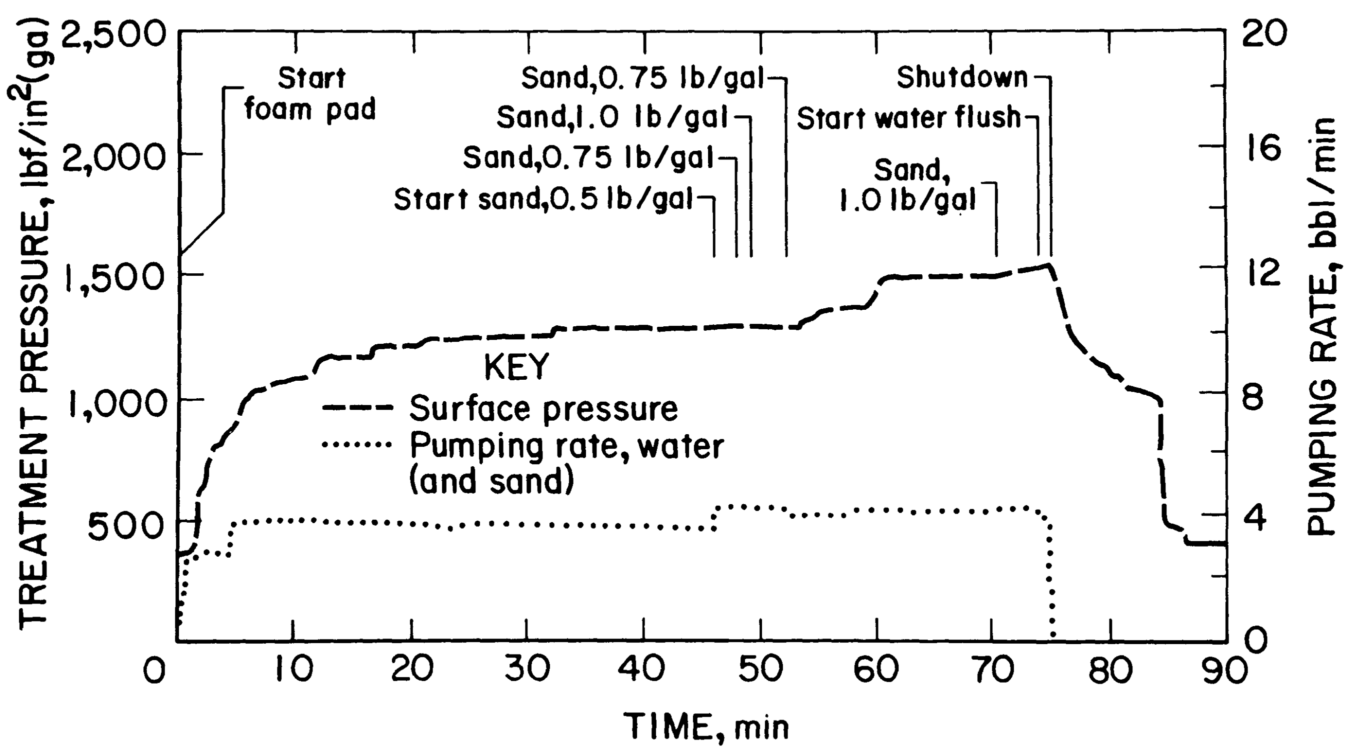

Figure 52.—Treatment record, borehole SC-1.

Underground Observations

The area around the presumed location of the borehole was mined through in April 1985. A directional survey run on the borehole was used to plot the coalbed intercept point, which was calculated to be approximately 35 ft north-northeast of the surface location and near the center of an entry (fig. 53). A thorough examination of the roof and ribs at the expected underground borehole location and all accessible entries in the area failed to reveal the borehole or any of the sand proppant used in the stimulation.

Examination of the area with the ultraviolet light revealed a substantial amount of green fluorescent material on the coal faces, and initially it was thought to be the green fluorescent paint used in the treatment. The fluorescence was generally restricted to short (less than 2-in) horizontal patches or bands in the coal. Closer examination revealed that the fluorescing material was actually naturally occurring resins that are common in the Cretaceous age coalbeds of the western United States. Blacklight surveys were then conducted at points as far as several thousand feet from the presumed location of the borehole, where there was essentially no possibility of the presence of paint from the stimulation. Green fluorescing material of the same character as was observed near the presumed borehole location was also seen at these remote locations.

There seemed to be more green fluorescence in the area of the presumed borehole location, so it is possible that some paint was actually present, but if so, it could not be distinguished from the naturally occurring fluorescent materials. It is also possible that there actually was more naturally occurring fluorescent material at this location, or that it was more noticeable because of the fresh, unweathered exposures. In any case, it would be advisable to check for any naturally occurring fluorescence before selecting a paint color for use in a stimulation treatment.

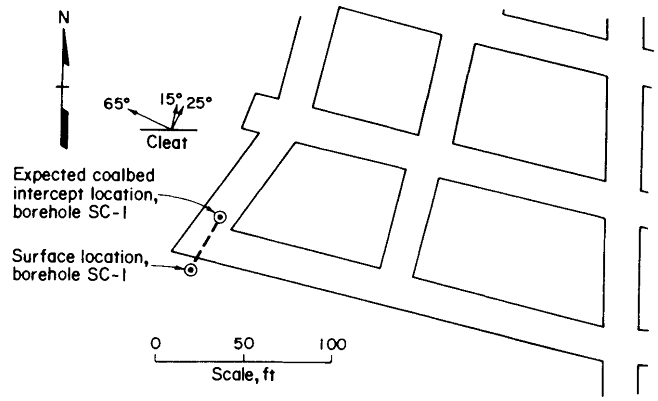

Figure 53.—Mine map, borehole SC-1.

If the borehole was located within the general area expected, and if the stimulation generally followed the face cleat orientation (N 65° W) as would be assumed, then a wing of the fracture would have a high probability of being intercepted by the available entries at the time of observation (fig. 53). The obvious incorrect presumed location of borehole SC-1 points out the need for accurate surveys (surface, underground, and borehole deviation) and the advantages of actually mining through the borehole in interpreting underground observations.

SUMMARY OF OBSERVATIONS

The areas affected by 22 Government-sponsored stimulation treatments in coalbeds have been mined through and observed underground. The underground observations have revealed a variety of conditions ranging from extensive vertical and horizontal sand-filled and/or paint-coated fractures to no discernible fractures. A summary of the treatment parameters and underground observations is given in tables 10 and 11. Eight of the treatments included the addition of fluorescent paint as an aid in locating and mapping the paths of fluid movement in the exposed coalbed and surrounding strata. With the paint, it was generally possible to trace the paths of fluid movements farther than the presence of the more obvious sand-filled fractures. It was also possible to identify additional zones of multiple fluid pathways. A good example of the additional traceable fracture length was observed at borehole DHM-6 (Oak Grove Mine, Alabama), where sand-filled fractures could be traced a maximum of 95 ft compared to paint-coated cleat observed 630 ft from the borehole.

When paint-coated fractures were identified using the ultraviolet light, the fracture width was essentially only the width of the naturally occurring cleat that had been penetrated. The cleat would not have been identified as a pathway for stimulation fluid without the presence of the paint. It is not known if the paint-coated cleat in fact represents a path of increased permeability that will enhance the flow of water and gas to the wellbore.

Most of the observed sand-filled and paint-coated vertical fractures penetrated or paralleled face cleat and occasionally butt cleat in the coalbed. It is interesting to note that the longest sand-filled vertical fracture (416 ft, borehole 1-NE, Illinois No. 6 Coalbed) did not parallel a cleat direction, but was approximately 30° from the butt cleat orientation. This may be the result of the influence of local horizontal stress fields or unobserved stairstepping, which gave an apparent orientation oblique to the cleat orientation. At several locations, fractures that paralleled the face cleat did not directly intercept the borehole if extended back from their point of observation. Apparently these treatment fluids followed a stairstep pathway through the coalbed, alternating along face and butt cleat, with only the face cleat fractures being observed on the exposed ribs and pillars.

Vertical sand-filled fractures were generally wider nearest the borehole and narrowed rapidly away from the borehole. The maximum lateral extent of sand-filled vertical fracture wings was generally short. Nine boreholes had sand-filled fracture wings with a maximum length of 30 ft or less, three boreholes had fracture wings 70 to 100 ft in length, and only four had wings over 100 ft in length. Zones of multiple, thin parallel sand-filled and/or paint-coated fractures are common near the boreholes. At increasing distances from the boreholes, the number of multiple vertical fractures usually decreases and only a single fracture remains. Vertical fractures also

Table 10.—Summary of stimulation treatment data

Borehole	Depth (top of coal), ft	Treatment	Fluid: Volume, gal	Fluid: Injection rate, bbl/min	Sand, lb	Surface pressure, lbf/in²(ga): Average	Surface pressure, lbf/in²(ga): Maximum
BLUE CREEK COALBED, OAK GROVE MINE, JEFFERSON COUNTY, AL							
TW-1	1,113.0	Gelled water	5,290	2 –10.5	2,500	650	1,775
TW-2	1,093.4	..do	3,500	8	4,000	2,400	2,500
TW-3	1,074.0	Foam	20,000	10	25,000	1,400	1,500
TW-4	1,065.0	..do	12,200	10	12,520	1,500	1,800
TW-5	1,145.0	..do	53,000	2 – 6	NAp	1,900	2,000
DHM-5	1,383.5	..do	40,866	7	NAp	850	950
DHM-6	1,238.6	..do	50,568	3 – 7	10,000	850	900
PITTSBURGH COALBED, VESTA NO. 5 MINE, WASHINGTON COUNTY, PA							
USBM-4	588.0	Gelled water	7,300	10.5	3,500	1,550	1,800
PITTSBURGH COALBED, EMERALD MINE, GREENE COUNTY, PA							
EM-5	764.0	Foam	[1]31,500	11.6	10,000	1,375	NR
EM-6	582.0	..do	[1]29,200	17.7	14,000	1,500	[2]2,150
EM-7	728.0	..do	[1]29,000	10.8	7,400	1,400	[2]NR
EM-8	646.0	..do	[1]42,000	10.8	12,800	1,050	1,200
EM-11	713.0	Kiel-water	54,600	19	10,000	1,200	NR
PITTSBURGH COALBED, CUMBERLAND MINE, GREENE COUNTY, PA							
CNG-1034	754.0	Foam	[3]21,840	10	23,500	1,200	NR
UPPER FREEPORT COALBED, LUCERNE NO. 6 MINE, INDIANA COUNTY, PA							
RP-1	626.5	Water	1,600	0.4– 7.4	NAp	NAp	1,260
RP-2	630.4	Foam	19,800	8	7,000	1,150	1,250
RP-3	634.6	..do	30,200	6	11,500	850	1,110
LOWER KITTANNING COALBED, KITT NO. 1 MINE, BARBOUR COUNTY, WV							
KE-2	660.0	Foam	23,500	8	3,300	NAp	[2]2,000
DGBH-5	637.0	..do	50,400	8	11,800	950	1,210
ILLINOIS NO. 6 COALBED, INLAND STEEL MINE, JEFFERSON COUNTY, IL							
1-NE	729.0	Gelled water	12,000	10	6,400	850	1,050
JAWBONE COALBED, McCLURE NO. 1 MINE, DICKENSON COUNTY, VA							
DG-1A	425.0	Foam	[4]35,300	16	28,000	NR	NR
ROCK CANYON COALBED, SOLDIER CANYON MINE, CARBON COUNTY, UT							
SC-1	684.0	Foam	50,000	16	15,000	1,350	1,500

NAp Not applicable.
NR Not reported.
[1] Plus 900-gal water pad.
[2] Screenout occurred.
[3] Plus 640-gal water flush.
[4] Plus 4,200-gal water pad.

Table 11.—Summary of underground observations for 22 intercepted stimulation treatments

Borehole	Hole location exposed	Fluorescent paint used	Max observed vertical wing length, ft: Sand filled	Max observed vertical wing length, ft: Paint coated	Max width vertical fracture, in	Zones of multiple vertical fractures	Max observed horizontal fracture length, ft: Sand filled	Max observed horizontal fracture length, ft: Paint coated	Multiple horizontal fracture planes	Roof penetration
TW-1	Yes	No.	5	NAp	½	Yes	NAp	NAp	NAp	Yes.
TW-2	Yes	No	16	NAp	4½	Yes	8	NAp	Yes	No.
TW-3	Yes	No	210	NAp	3/16	No	NAp	NAp	NAp	Yes.
TW-4	Yes	No	220	NAp	3/16	No	NAp	NAp	NAp	Yes.
TW-5	Yes	Yes	NAp	370	Cleat	Yes	NAp	230	Yes	Yes.
DHM-5	No	Yes	NAp	340	Cleat	Yes	NAp	NAp	NAp	Yes.
DHM-6	Yes	Yes	95	630	1/16	Yes	NAp	NAp	NAp	Yes.
USBM-4	Yes	No	20	NAp	2½	Yes	NAp	NAp	NAp	No.
EM-5	No	No	140	NAp	1½	No	50	NAp	No	No.
EM-6	Yes	No	10	NAp	2½	Yes	10	NAp	Yes	Yes.
EM-7	Yes	No	18	NAp	½	No	NAp	NAp	NAp	No.
EM-8	No	No	55	NAp	3/16	Yes	115	NAp	Yes	Yes.
EM-11	No	No	NAp	NAp	NAp	NAp	110	NAp	No	Yes.
CNG-1034	No	No	100	NAp	¼	No	NAp	NAp	NAp	No.
RP-1	Yes	Yes	[1]2	2	1/16	Yes	NAp	35	No	No.
RP-2	Yes	Yes	30	67	½	Yes	17	265	Yes	No.
RP-3	Yes	Yes	20	130	1	Yes	200	200	Yes	No.
KE-2	No	Yes	NAp	85	Cleat	No	NAp	100	No	No.
DGBH-5	No	No	72	NAp	½	Yes	105	NAp	No	No.
1-NE	No	No	416	NAp	3/8	No	NAp	NAp	NAp	Yes.
DG-1A	Yes	No	20	NAp	5/8	NR	250	NAp	Yes	No.
SC-1	No	Yes	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp.

NAp Not applicable. NR Not reported. [1]Sand from fill at bottom of hole, not from treatment.

commonly do not extend the entire height of the coalbed, but are found in only part of the coalbed. In the Blue Creek Coalbed, when fractures did not extend the entire height of the coalbed they were usually present in the upper part, and less commonly, only in the lower part of the coalbed. This may be related to variations in the physical character of the Blue Creek Coalbed, which is commonly more friable and "soft" in the upper part.

It has been suggested (*9, 28-29*) that gelled water stimulation treatments with sand proppant would theoretically produce relatively short, wide, sand-filled vertical fractures and foam treatments would produce longer, narrow, sand-filled fractures. Only four of the treatments observed underground used gelled water as the treatment fluid and therefore a definitive statement relating the relative differences between the character of fractures resulting from the different fluids is not possible. However, the widest sand-filled fracture observed (4½ in, borehole TW-2) was from a gelled water treatment. A 2½-in-wide sand-filled fracture was also observed for the gelled water treatment on borehole USBM-4, but a 2½-in-wide sand-filled fracture was also observed for the foam treatment on borehole EM-6. The longest sand-filled vertical fracture observed (416 ft, borehole 1-NE) was also from a gelled water treatment where short fractures would be expected.

The type of stimulation fluid has some influence on the character of the induced fractures, as do other factors such as treatment volume, injection rate, and depth and physical characteristics of the coalbed. Larger volume treatments tended to have more observable fractures as was seen in the three progressively larger treatments in the Upper Freeport Coalbed (boreholes RP-1, RP-2, and RP-3). Boreholes TW-5 and DHM-6, which had two of the largest volume treatments also had some of the most extensive networks of fractures.

The physical properties of the coalbed seemed to have some influence on the propagation of fractures. Many of the vertical fractures in the Blue Creek Coalbed were present only in the more friable upper part. The vertical sand-filled fractures at borehole TW-2 were located in the bottom "hard" part of the Blue Creek Coalbed and inclined and became horizontal at or near the interface between the lower "hard" part and the upper "soft" friable part. The Upper Freeport Coalbed (boreholes RP-1, RP-2, and RP-3) had a distinct shale parting near the top of the coalbed. In some cases the parting acted as a barrier to the upward growth of fractures, but it was more commonly penetrated by the vertical fractures, which then became horizontal at the interface at the top of the parting and base of the upper coal bench. A distinct "shaley" band in the Pittsburgh Coalbed at borehole EM-8 was generally penetrated by the vertical fractures that continued vertical above, but in one instance the fracture became horizontal above the band. It was also common to see small horizontal offsets in the vertical propagation of the fractures as different layers or bedding planes in the coalbed were encountered. These offsets occasionally resulted in an inclined or sinuous appearance to the "vertical" fracture. While the physical properties of the coalbed seemed to have some influence on the character of the fractures, that influence was variable and could not be considered predictable.

A horizontal fracture was discernable in approximately half of the mined through stimulation treatments. Five of eight treatments that used fluorescent paint and seven additional treatments that did not use paint had identifiable horizontal fractures. It is generally thought that at increasing depths (overburden pressure) the incidence of horizontal fracturing decreases. A horizontal fracture was found in stimulated coalbeds as deep as 1,145 ft in the Blue Creek Coalbed (borehole TW-5). This fracture was only identifiable as paint coatings since no sand was used in the treatment on borehole TW-5. The two treatments with fluorescent paint in the Blue Creek Coalbed that did not have identifiable horizontal fractures were, at depths of 1,384 ft (borehole DHM-5) and 1,239 ft (borehole DHM-6), the deepest stimulations mined through. The deepest stimulation with a sand-filled horizontal fracture was 1,093 ft in the Blue Creek Coalbed at borehole TW-2, however, the rest of the sand-filled horizontal fractures were found at depths of 400 to 800 ft. It seems likely that additional horizontal fractures (or fluid pathways) would have been observed, especially in the shallow coalbeds, if fluorescent paint had been used in more treatments.

The most common location for the horizontal fractures is at the top of the coalbed at the interface with the roof rock. Occasionally horizontal fractures are found along other distinct interfaces such as shale partings, shaley or hard, dense bands, or rider coals in the immediate roof rock. The distribution of sand or paint on horizontal surfaces was generally erratic (partially because of the difficulty in mapping their entire area), but in two cases (boreholes RP-2 and RP-3) there was some suggestion that there was a correlation between cleat orientation and horizontal lobes of paint. Also at borehole TW-5 the horizontal (and vertical) fractures covered an area with a general elliptical shape with the long axis parallel to the face cleat orientation. Multiple horizontal fractures on different planes have been observed in several cases.

The sand-filled horizontal fractures are generally thickest near the wellbore (maximum of 1 in), usually are thin (less than ½ in) but quite variable in thickness along short lateral distances, and may be discontinuous along an exposed rib. The maximum lateral extents for sand-filled horizontal fractures were 250 ft in the Jawbone Coalbed (borehole DG-1A) and 200 ft in the Upper Freeport Coalbed (borehole RP-3). The maximum lateral extents for paint-coated horizontal fractures were 265 and 200 ft in the Upper Freeport Coalbed (boreholes RP-2 and RP-3) and 230 ft in the Blue Creek Coalbed (borehole TW-5).

Penetration by fluids and/or sand proppant into strata directly overlying the main bench of coal has been observed in nearly half of the treatments intercepted underground. In addressing the significance of roof penetration it is necessary to point out that roof penetration does not necessarily equate to roof damage or an adverse effect on mining. There have been no roof falls attributed to the penetration of stimulation fluids into roof strata from Government-sponsored treatments. Lambert (*9*) did report that supplementary roof support was installed as a precautionary measure in the vicinity of borehole TW-3 at the Oak Grove Mine, where both the mined Blue Creek Coalbed and the overlying Mary Lee Coalbed, 5½ ft above, were stimulated and where mine management observed "roof movement" along a nearby rib. According to Lambert (*9*), the area was mined through "without experiencing any roof fall during mining operations."

Except for the Blue Creek Coalbed, most of the penetrations of strata above the main coal bench have been fairly limited in vertical and/or horizontal extent. In several cases, penetration of strata above the Blue Creek Coalbed was observed at locations a hundred feet or more from a borehole. The reason for the more extensive roof penetrations is not conclusively known, but may be related to the complex structural history of the area. Recent in situ state of stress (ISSOS) tests conducted near the Oak Grove Mine indicated lower in situ stress values for the rocks surrounding the Mary Lee-Blue Creek Coalbeds than measured in the coal (*30*). In the absence of a stress barrier or mechanical property barrier, upward fracture breakout is more likely. Upward fracture breakout from this coal section was reported during the ISSOS testing near the Oak Grove Mine. The presence of naturally occurring roof joints coupled with lower or similar in situ stresses above the coal probably influenced the extent of roof penetration at the Oak Grove Mine.

In several cases the strata penetrated above coalbeds have been weak, thin shales below rider coals, and the fractures have been contained in strata that was generally mined along with the main bench of coal throughout the mine to prevent it from deteriorating and falling at a later time. Thus such strata penetration should not really be considered roof penetration.

Part of the problem of acceptance of the use of stimulated vertical boreholes to remove gas from coalbeds prior to mining may be related to the use of the terms "fracture," "fracturing," and "breakdown," which perhaps suggest a catastrophic breakup of the strata treated. The evidence from direct underground observation and many of the treatment records (including those from boreholes not mined through) suggest that new fractures are seldom created, but rather naturally occurring planes of weakness (cleat, joints, or bed boundaries) are entered and widened to varying degrees. In most cases the penetration of strata overlying the main coal bench has been attributed to the invasion of preexisting joints, as evidenced by similar joints of the same general character and orientation occurring throughout a mine.

CONCLUSIONS

It is impossible to guarantee that a stimulation treatment in a coalbed will not adversely affect mining in some way. However, the underground evidence and experience to date suggests that the probability of adversely affecting mining conditions is minimal. The use of prestimulation strata characterization tests and informed treatment design and controlled implementation (primarily injection rates and therefore treatment pressure) can probably further minimize the chance of adverse mining conditions.

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APPENDIX.—ACQUISITION AND LIMITATIONS OF STIMULATION TREATMENT DATA

There are large measurement uncertainties associated with the recording of any hydraulic stimulation treatment. The reader should keep this fact firmly in mind when reading the treatment records reproduced in this report. In most cases where two or more independent records of treatment parameters were kept, these records seldom agreed, although supposedly all of the information in the records came from the same instruments at the same time. The records available from the treatments include the recorded pressure and water flow data (and any other parameters that may have been recorded continuously), the notes usually made by the engineer in charge of the treatment, and in some cases notes made by Government or other personnel during the treatment.

Two measurements commonly are recorded during every hydraulic stimulation treatment. These are the water pumping rate at the pump truck and the surface pressure. In addition, during some treatments, additional information can be, but typically is not, recorded. This additional information includes the density of the fracturing fluid at the pump truck, the density of the fluid as it goes into the wellhead, the bottom hole pressure, and the fracturing fluid flow rate at the wellhead.

The liquid pumping rates are determined by counting pump strokes and multiplying by a factor based upon the cylinder volume and the pump efficiency. The accuracy of the measurements is probably about 5 pct. Nitrogen for foam fracturing treatments is carried as a liquid, so liquid flowmeters are used to measure the nitrogen flow rate before it is heated and vaporized. The accuracy of the meters is not commonly given, but is probably no better than 5 pct. Surface pressures may be measured using a variety of types of instruments. Pressure should be the most accurately determined quantity of any measured during a treatment. It should be possible to determine treating pressures to an accuracy of 1 pct (or within 10 lbf/in^2 per 1,000 lbf/in^2(ga)). In practice an accuracy of ± 100 lbf/in^2 is probably very good.

The fluid density is determined by using a densitometer employing a gamma ray source and a detector that counts the gamma rays returning through the fluid. Most pump trucks carry one to allow measurement and control of cement density while cementing casing in oil and gas wells. The instruments are calibrated for higher densities than those of fracturing fluids, but they should still be usable, and they were used to measure sand concentrations during the treatments of some of the wells described in this report.

The exact method of measuring the sand injection rate is unclear, but probably it is estimated from the density of the sand and water mixture at the truck. The method of determining the total weight of sand injected at the end of the treatment appears to be to take the difference between the original sand volume carried to the site and the remaining sand volume after completion of the treatment. If this is the case, then the sand injection rates given during the course of the treatments (and shown on some of the treatment records in this report) are estimates only and do not necessarily give accurate sand injection rates.

Bottom hole pressure may be measured in two different ways. The most accurate method, but for practical reasons the most difficult and expensive to employ, is to place a remote-reading pressure gauge at the bottom of the hole. A simpler method is to run tubing in the hole to the depth of the coalbed and fill the tubing with water. At the wellhead a pressure gauge is then installed on the top of the tubing. The pressure gauge on top of the tubing then reads the bottom hole pressure less the hydrostatic pressure of the water in the tubing. The hydrostatic pressure can then be added back in to obtain the bottom hole pressure. The treatment is conducted by pumping fluids down the annulus between the casing and the tubing. The method suffers from the drawback that the tubing can be sealed off by coal or sand, or gas can enter the tubing, causing incorrect pressure readings. This method was used in the wells described in this report where bottom hole pressures are given. It should be kept in mind that bottom hole pressures can differ from surface pressures because of the hydrostatic pressure of the treating fluid in the borehole and because of friction losses due to pumping. These two sources of pressure differences have opposite effects, so the bottom hole pressure can be less than, greater than, or the same as the surface pressure, depending upon the conditions of the treatment.

During gelled water treatments, all measurements at the wellhead will be the same as those at the truck and are redundant. However when foam is being pumped, it is necessary to determine the density and flow rate of both the water and sand mixture leaving the pump truck and of the foam mixture after the nitrogen has been added (downstream of the pump truck) in order to determine the true volumetric pumping rate of the foam (a water, nitrogen, and sand mixture). This additional information has been obtained for some of the wells described in this report, but in general is not available for most foam-stimulated wells.

Because the foam mixture is a compressible fluid, its actual (volumetric) pumping rate is controlled by the pressure. During a typical foam stimulation treatment the liquid and gas flow rates are measured separately and the volumes are then added, with the nitrogen flow rate being determined at the surface pressure. An attempt is generally made to maintain a foam quality of 75 pct (or 75 pct nitrogen by volume and 25 pct sand and water by volume) at the surface for optimum sand carrying capacity. This is done by estimating the average treating pressure at the beginning of the treatment and calculating the nitrogen required to give a gas volume of 75 pct of the total foam volume.

Occasionally during a treatment as pressures change, the nitrogen rate is corrected, but difficulties in adjusting the rate of the nitrogen flow make service company personnel reluctant to continually adjust the nitrogen flow rate to maintain the proper foam quality. Because of this, large errors in the estimated volume of the treatment can occur. The estimated treating rate is obtained by multiplying the water rate by a factor of 4. This is only correct as long as the foam quality is 75 pct. However if the pressure deviates from the initial planned treating pressure (or indeed if the estimate was incorrect to begin with) then the foam quality may never be 75 pct.

Foam qualities as low as 50 pct have been observed and 60 pct is common. If a treatment planned for a 75-pct foam quality is actually run at 50-pct quality, then the true foam volume pumped will only be one half of that initially planned. A planned 50,000-gal foam treatment could then become a 25,000-gal treatment with the same material masses pumped into the formation. In addition, all of these measurements are made at surface conditions and the foam quality is adjusted for surface conditions. However it is the bottom hole foam quality that really should be maintained at 75 pct and without knowing the bottom hole pressure there is no guarantee that the bottom hole foam quality is correct.

As an example, consider a treatment planned for a foam injection rate of 10 bbl/min at a pressure of 500 lbf/in^2(abs). The required nitrogen rate to maintain a 75-pct quality at this pressure is 185 std ft^3/min. If the pressure increases to 1,000 lbf/in^2(abs) during the treatment, the required nitrogen volume is doubled to 370 std ft^3/min. If the nitrogen rate is not increased, which is commonly the case, then the foam quality is reduced to 50 pct and the actual pumping rate becomes 5 bbl/min. This effect is more pronounced at the lower pressures used in shallow coalbed wells than in deeper holes, which require higher treating pressures. For instance it would require a pressure increase from 1,000 to 2,100 lbf/in^2(abs) to necessitate another doubling of the nitrogen rate. Pressure changes of 500 lbf/in^2 are common during the course of a foam stimulation, but changes of 1,000 lbf/in^2 occur much less frequently.

The fact that the measurement errors can be much larger at low pressures is a problem because the service company personnel, being familiar with oil and gas wells treated at much higher pressures are less likely to consider it necessary to adjust nitrogen rates during the course of a treatment. Their reluctance to adjust the nitrogen rate is also increased because it is difficult to adjust the nitrogen rate and because the very act of increasing the nitrogen rate leads to changes in volumetric flow rate, which can increase the pressure leading to a need for further increases in nitrogen flow. It may take some time to reach an equilibrium flow rate. Starting with too much nitrogen is not the answer because at high qualities (possibly 85 pct and certainly 90 pct) the foam begins to lose its sand carrying properties.

The measurements of pumping rates, pressures, densities, and sand weights are not always highly accurate. In the few cases observed by the Bureau where two or more independent measurements of the same quantity were available, the measurements disagreed by a large amount. In the case of a treatment at the Soldier Canyon Mine, Utah, at one point there were three surface pressure readings available ranging from about 1,500 to 2,000 lbf/in^2(ga). None of the three gauges agreed and two showed differences of 300 lbf/in^2(ga) (a 20-pct difference). Pressure should be the easiest treatment parameter to measure accurately. Pumping rates, densities, and nitrogen rates are more difficult to measure accurately and it is therefore reasonable to have even greater suspicion of treatment volumes computed from measurements of these parameters.

One way to potentially improve the reliability of the treatment records is for customers to discuss the planned treatment and the measuring techniques in detail with the service company sales engineers well in advance of the treatment and with the field engineer just prior to the treatment. The actual effectiveness of this scenario is probably limited, however. The most important individual to discuss the treatment with prior to its start is usually the busiest and most difficult to arrange time to talk to. In addition, this individual may in some cases misinterpret an interest in the details of a treatment as suggesting a lack of trust on the customer's part. Requests for information on the accuracy of gauges and meters may be met with comments that the measurements are exactly correct, and that there are no measurement errors, or the engineer may simply not know the accuracy of his or her equipment. The same is true of a request for information on the exact method of operation of the equipment and the mode of measurement of the treatment parameters. These parameters can vary with the equipment used and can only be determined with certainty at the job site by discussion with the field engineers.

One important area where improvement is perhaps more likely is in recordkeeping. On many of the records studied for this report it was found that service company personnel tended to leave out scale information on the pressure and flow rate charts. The scale information most often left off was the time scale. Customers should be careful to request that this information be placed on these records or to note the scales themselves and add them to the records when they obtain them. It should also be made clear to the service company personnel by the customers that they want copies of these records, since copies are always made, but not necessarily given to the customer unless requested. It is also important that the customers keep their own notes as a check on the accuracy of the service company field engineer's field notes. The job ticket used for computing the treatment cost should not be trusted to give an accurate history of the treatment, since this record may be altered in the field for various reasons, such as giving unadvertised job discounts.

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