UNDERGROUND OBSERVATIONS OF MINED-THROUGH STIMULATION TREATMENTS OF COALBEDS

by William P. Diamond[1]

ABSTRACT

Twenty-two government-sponsored stimulation treatments have been mined through underground to determine the effects on the coalbed and roof strata. Vertical fractures in coalbeds were discernible for most treatments, and sand-propped portions were usually short in lateral extent. Horizontal fractures, present in about half the treatments, were found generally within bedding planes, most commonly on top of the coalbed. For treatments to which fluorescent paint had been added, evidence of stimulation fluid movement could generally be traced beyond the maximum extent of sand-filled fractures. Penetration of strata overlying the coalbeds was observed in nearly half of the treatments intercepted, but most of these have been interpreted as penetrations into preexisting planes of structural weakness. No roof falls or adverse mining conditions were encountered that could be attributed to the stimulations.

INTRODUCTION

A total of 22 government-sponsored stimulation treatments in gas-bearing coalbeds have been intercepted by underground mining. Twenty-one of these interceptions were in the eastern United States (ten in Pennsylvania, seven in Alabama, two in West Virginia, and one each in Illinois and Virginia); only one in the western United States (Utah) was available for investigation. These underground interceptions provided a unique opportunity to observe directly the actual effects of hydraulic stimulation treatments on coalbeds and surrounding strata. This report details observations previously presented in various forms by the U.S. Bureau of Mines, U.S. Department of Energy, and their contractors as well as information not previously reported.

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 operation have been shown to be very effective in providing short-term, immediate relief from high methane emissions (Finfinger and Cervik, 1980; Hagood and others, 1983; Perry and others, 1978; Thakur and Poundstone, 1980; Von Schonfeldt and others, 1982). Although this technique has been widely accepted in the coal mining industry, it does require careful 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 (Dunn, 1984; Elder, 1977; Lambert and others, 1980; Steidl, 1978; Stubbs and others, 1979). Compared to horizontal boreholes, the vertical borehole technique has the additional advantage 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 commercial gas production in the Black Warrior basin of Alabama (Dunn, 1984; Lambert and others, 1980; Stubbs and others, 1979), the technique has been underutilized. The primary reason for this appears to be a combination of economic conditions within the coal industry, legal questions concerning ownership of coalbed gas, and the fear of roof damage from stimulation treatments. The important question of potential roof damage will be addressed in this paper.

Underground evaluation of areas surrounding stimulated coalbed methane boreholes is an important step in developing stimulation treatments that are efficient yet will not adversely affect mining. By directly observing the effects of a particular stimulation design on a coalbed and surrounding strata early in the development stages of a methane drainage program, and by evaluating those observations in light of thorough geologic characterization, one can obtain valuable information on subsequent drilling and stimulation. It is important to note that what is seen underground depends upon the area exposed by mining and the timing of observations with respect to the advance of entries. Obviously, once a volume of coal is mined, anything contained in that coal is forever lost for direct examination.

Because of the large volume of completion, treatment, and mine-through data accumulated from most of the stimulations, only a synopsis of the results from all stimulations can be presented here. Detailed information is available either from the referenced publications or from a new Bureau of Mines compilation and analysis of all pertinent data associated with the 22 treatments (Diamond and Oyler, in press).

UNDERGROUND OBSERVATIONS

Underground observations have revealed a variety of fracturing conditions, ranging from extensive vertical and horizontal sand-filled and/or fluorescent-paint-coated fractures to no discernible fractures. Fluorescent paint was added to eight treatments to aid in locating and mapping the paths of fluid movement through the coal and surrounding strata. Tables 1 and 2 summarize the treatment parameters and underground observations.

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Vertical Fractures

Vertical sand-filled fractures generally were wide nearest the borehole but narrowed rapidly away from the borehole. Maximum lateral extents of sand-filled vertical fracture wings were generally short. Nine boreholes had sand-filled fracture wings with maximum lengths of 30 ft; three boreholes had fracture wing lengths of 70 to 100 ft; and only four had win lengths over 100 ft (Figures 1, 2 and 3).

For those treatments to which fluorescent paint had added, fractures usually could be traced as paint-coated beyond their maximum sand-filled extent. These cleat could not have been identified as pathways for stimulation fluid without the presence of the paint. However, it is not known

Table 1. Summary of data for 22 intercepted stimulation treatments.

Coalbed, Mine, Borehole	Depth to Top of Coal (ft)	Treatment Type	Treatment Fluid: Volume (gal)	Treatment Fluid: Injection Rate (BPM)	Sand Weight (lb)	Surface Pressure (psig): Average	Surface Pressure (psig): Maximum
BLUE CREEK COALBED, OAK GROVE MINE, JEFFERSON COUNTY, ALABAMA							
TW-1	1,113.0	Gel/Water	5,290	2-10.5	2,500	650	1,775
TW-2	1,093.4	Gel/Water	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	Foam	12,200	10	12,250	1,500	1,800
TW-5	1,145.0	Foam	53,000	2-6	—	1,900	2,000
DHM-5	1,383.5	Foam	40,866	7	—	850	950
DHM-6	1,238.6	Foam	50,568	3-7	10,000	850	900
PITTSBURGH COALBED, VESTA NO. 5 MINE, WASHINGTON COUNTY, PENNSYLVANIA							
USBM-4	588.0	Gel/Water	7,300	10.5	3,500	1,550	1,800
PITTSBURGH COALBED, EMERALD MINE, GREEN COUNTY, PENNSYLVANIA							
EM-5	764.0	Foam	31,500[a]	11.6	10,000	1,375	NR
EM-6	582.0	Foam	29,200[a]	17.7	14,000	1,500	2,150[b]
EM-7	728.0	Foam	29,000[a]	10.8	7,400	1,400	NR[b]
EM-8	646.0	Foam	42,000[a]	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, GREEN COUNTY, PENNSYLVANIA							
CNG-1034	754.0	Foam	21,840[c]	10	23,500	1,200	NR
UPPER FREEPORT COALBED, LUCERNE NO. 6 MINE, INDIANA COUNTY, PENNSYLVANIA							
RP-1	626.5	Water	1,600	0.4-7.4	—	—	1,260
RP-2	630.4	Foam	19,800	8	7,000	1,150	1,250
RP-3	634.6	Foam	30,200	6	11,500	850	1,110
LOWER KITTANNING COALBED, KITT NO. 1 MINE, BARBOUR COUNTY, WEST VIRGINIA							
KE-2	660.0	Foam	23,500	8	3,300	—	2,000[b]
DGBH-5	637.3	Foam	50,400	8	11,800	950	1,210
ILLINOIS NO. 6 COALBED, INLAND STEEL MINE, JEFFERSON COUNTY, ILLINOIS							
1-NE	729.0	Gel/Water	12,000	10	6,400	850	1,050
JAWBONE COALBED, MCCLURE NO. 1 MINE, DICKENSON COUNTY, VIRGINIA							
DG-1A	425.0	Foam	35,300[d]	16	28,000	NR	NR
ROCK CANYON COALBED, SOLDIER CANYON MINE, CARBON COUNTY, UTAH							
SC-1	684.0	Foam	50,000	16	15,000	1,350	1,500

[a] Plus 900-gal water pad.
[b] Screenout occurred.
[c] Plus 640-gal water flush.
[d] Plus 4,200-gal water pad.

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Table 2. Summary of underground observations for 22 intercepted stimulation treatments.

Borehole	Hole Location Exposed	Fluorescent Paint Used	Maximum Observed Vertical Wing Length (ft) Sand-Filled	Paint-Coated	Maximum Vertical Fracture Width (in.)	Zones of Multiple Vertical Fractures	Maximum Observed Horizontal Fracture Length (ft) Sand-Filled	Paint-Coated	Multiple Horizontal Fracture Planes	Roof Penetration
TW-1	Yes	No	5	—	1/2	Yes	—	—	—	Yes
TW-2	Yes	No	16	—	4 1/2	Yes	8	—	Yes	No
TW-3	Yes	No	210	—	3/16	No	—	—	—	Yes
TW-4	Yes	No	220	—	3/16	No	—	—	—	Yes
TW-5	Yes	Yes	—	370	Cleat	Yes	—	230	Yes	Yes
DHM-5	No	Yes	—	340	Cleat	Yes	—	—	—	Yes
DHM-6	Yes	Yes	95	630	1/16	Yes	—	—	—	Yes
USBM-4	Yes	No	20	—	2 1/2	Yes	—	—	—	No
EM-5	No	No	140	—	1 1/2	No	50	—	No	No
EM-6	Yes	No	10	—	2 1/2	Yes	10	—	Yes	Yes
EM-7	Yes	No	18	—	1/2	No	—	—	—	No
EM-8	No	No	55	—	3/16	Yes	115	—	Yes	Yes
EM-11	No	No	—	—	—	—	110	—	No	Yes
CNG-1034	No	No	100	—	1/4	No	—	—	—	No
RP-1	Yes	Yes	2[a]	2	1/16	Yes	—	35	No	No
RP-2	Yes	Yes	30	67	1/2	Yes	17	265	Yes	No
RP-3	Yes	Yes	20	130	1	Yes	200	200	Yes	No
KE-2	No	Yes	—	85	Cleat	No	—	100	No	No
DGBH-5	No	No	72	—	1/2	Yes	105	—	No	No
1-NE	No	No	416	—	3/8	No	—	—	—	Yes
DG-1A	Yes	No	20	—	5/8	NR	250	—	Yes	No
SC-1	No	Yes	—	—	—	—	—	—	—	—

[a] Sand from fill at bottom of hole, not from treatment.

whether or not the fractures represented by paint-coated cleat represent paths of increased permeability that can enhance the flow of water and gas to the wellbore. An excellent example of additional traceable fracture length was observed at borehole DHM-6 in the Blue Creek Coalbed, where sand-filled fractures could be traced a maximum 95 ft southwestward from the borehole, compared to paint-coated cleat observed 630 ft to the northeast (Figure 4).

The most extensive paint-coated paths of fluid movement were observed in the vicinity of boreholes RP-2 and RP-3 in the Upper Freeport Coalbed (Figure 5) and borehole TW-5 in the Blue Creek Coalbed (Figure 6). Fluid volume appears to have influenced the extent of fluid movement in that a greater number of fractures were associated with borehole RP-3, whose treatment volume was approximately one-third larger than that for RP-2. Borehole TW-5 also had one of the largest volume treatments.

Zones of multiple parallel sand-filled and/or paint-coated fractures commonly occur near the boreholes. Progressively farther from the boreholes, the number of multiple vertical fractures usually decreased to a point at which only a single fracture remained. The fluorescent paint was particularly useful in identifying multiple fluid pathways that were essentially only the width of a cleat (Figure 7). The occur-

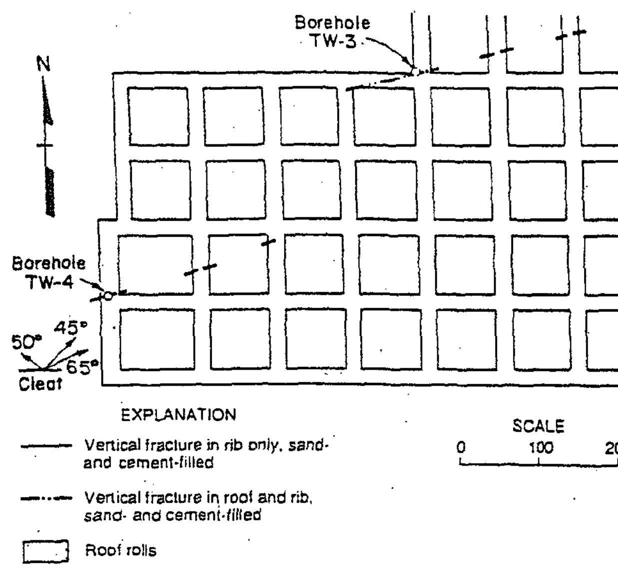

Figure 1. Locations of vertical fractures from boreho[les] TW-3 and TW-4, Blue Creek Coalbed, Oak Grove mi[ne], Jefferson County, Alabama.

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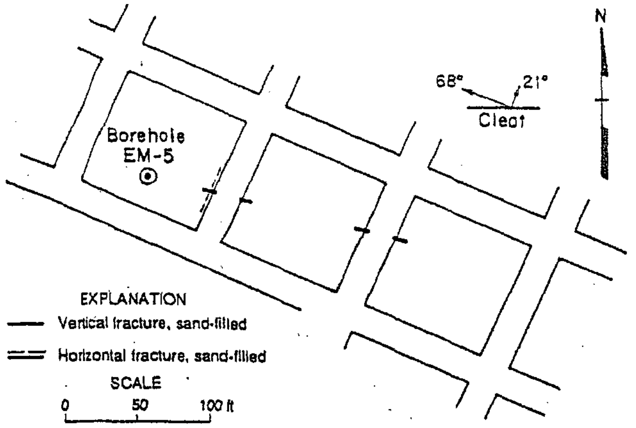

Figure 2. Location of vertical and horizontal fractures from borehole EM-5, Pittsburgh Coalbed, Emerald mine, Greene County, Pennsylvania.

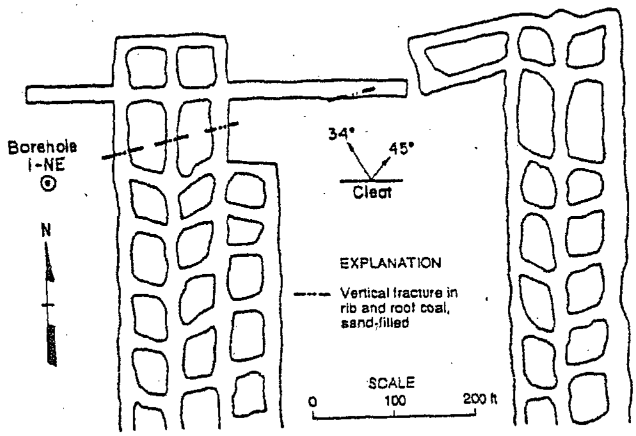

Figure 3. Location of vertical fracture from borehole 1-NE, Illinois No. 6 Coalbed, Inland Steel mine, Jefferson County, Illinois.

rence of multiple fractures correlates with coal friability—fracture zones were more prevalent in friable coalbeds, such as the Upper Freeport (Figure 7) and the Blue Creek (Figure 8). On the other hand, single, wide, sand-filled fractures were predominant in hard, blocky coalbeds, such as the Pittsburgh. These observations may, however, be somewhat biased because none of the treatments in the Pittsburgh Coalbed contained paint, and many zones of multiple fractures in the friable coalbeds were identifiable only as paint-coated cleat. One must therefore exercise caution when comparing the results of treatments with and without paint.

Vertical fractures commonly did not extend the entire seam height but rather were found in only part of the coalbed. In the Blue Creek Coalbed, for example, fractures not extending the entire coalbed height usually occurred in the upper part and less commonly only in the lower part. This tendency may be attributable to variations in the physical character of the Blue Creek Coalbed, which is commonly more friable and "soft" in the upper part.

Most of the observed sand-filled and paint-coated vertical fractures penetrated or paralleled the coal's face cleat and occasionally butt cleat. The longest sand-filled vertical fracture (416 ft, Illinois No. 6 Coalbed, borehole 1-NE) notably did not parallel either cleat direction but trended approximately 30° from the butt cleat orientation (Figure 3). This variant trend may have resulted from the influence of local horizontal stress fields; or it may actually be an unobserved stair-stepping of the fracture along both the face and butt cleat, which results in an apparent oblique orientation. At several locations, fractures paralleling the face cleat did not directly intercept the borehole when projected from their points of observation. Apparently these treatment fluids followed stair-step pathways through the coalbed, with only the face cleat fractures observable on exposed ribs and pillars.

Perkins and Kern (1961), Halliburton Services (1971), and Lambert and others (1980) have suggested that gelled-water stimulation treatments with sand proppant would theoretically produce relatively short, wide, sand-filled vertical fractures, and foam treatments would produce longer, narrower, sand-filled fractures. The widest sand-filled fracture observed (4½ in., borehole TW-2) was from a gelled-water treatment in the Blue Creek Coalbed (Figure 8). A 2½-in.

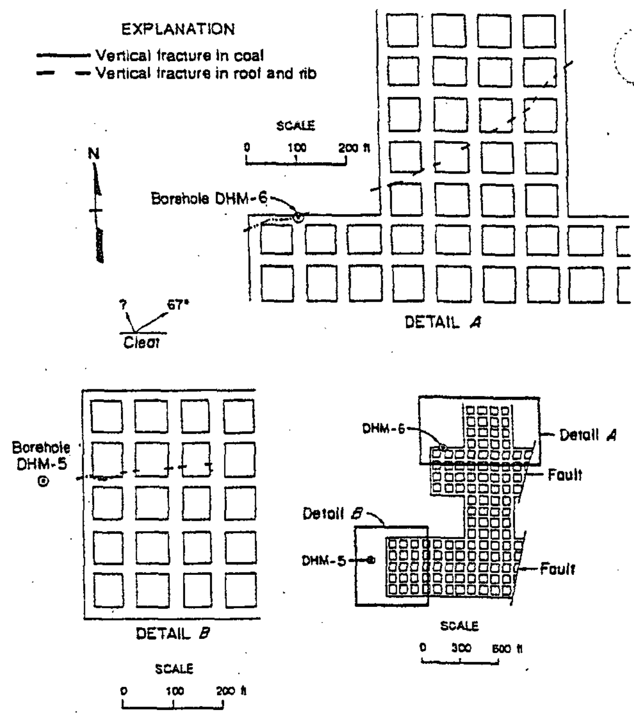

Figure 4. Locations of vertical fractures from boreholes DHM-5 and DHM-6, Blue Creek Coalbed, Oak Grove mine, Jefferson County, Alabama.

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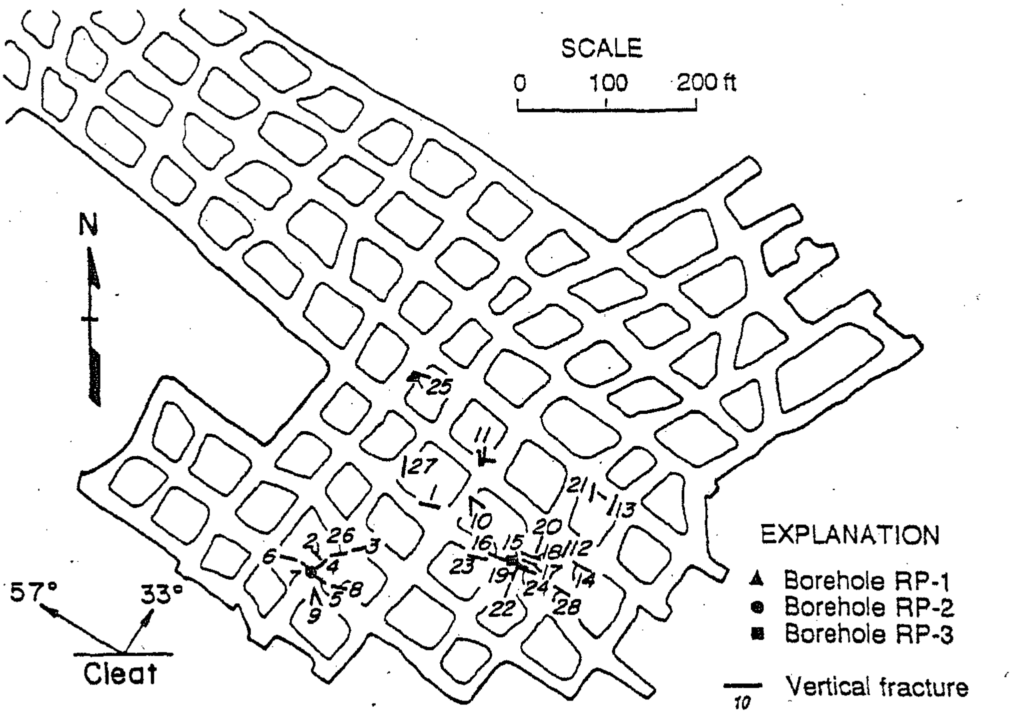

Figure 5. Locations of vertical fractures around boreholes RP-1, RP-2, and RP-3, Upper Freeport Coalbed, Lucerne No. 6 mine, Indiana County, Pennsylvania.

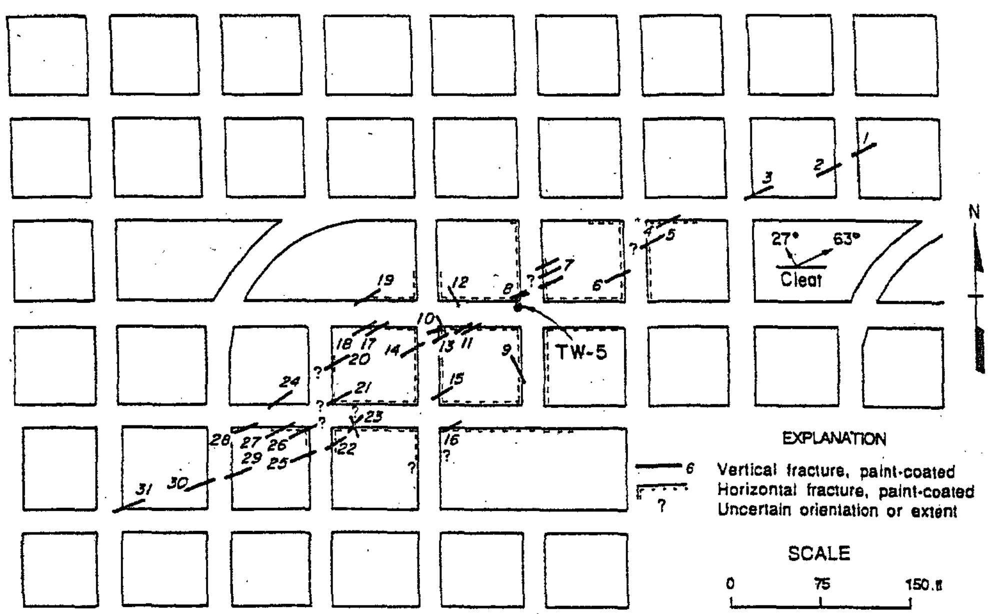

Figure 6. Locations of vertical and horizontal fractures around borehole TW-5, Blue Creek Coalbed, Oak Grove mine, Jefferson County, Alabama.

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sand-filled fracture was observed for the gelled-water treatment of borehole USBM-4 in the Pittsburgh Coalbed (Elder, 1977). However, a 2½-in. sand-filled fracture also was observed for the foam treatment on borehole EM-6 in the Pittsburgh Coalbed (Steidl, 1978; Lambert and others, 1980). Furthermore, the longest sand-filled vertical fracture observed (419 ft, borehole 1-NE) resulted from a gelled-water treatment in the Illinois No. 6 Coalbed (Figure 3), where short fractures would have been expected. Because only four treatments observed underground used gelled water, a definitive statement correlating fracture character with stimulation fluid type is not possible.

Horizontal Fractures

In situ state-of-stress measurements at GRI's Rock Creek site in Alabama have shown that when overburden (vertical) stresses are significantly less than horizontal stresses in shallow coals, horizontal fracturing likely will result (Popovich, 1985). It is generally thought that with increasing depth and overburden stress, the incidence of horizontal fracturing decreases.

In this study horizontal fractures were discernible in approximately half of the mined-through stimulation treatments, including five of the eight treatments that used fluorescent paint and seven others without paint (Table 2). Nearly all sand-filled horizontal fractures were found at depths of 400 to 800 ft. One horizontal fracture was found in stimulated coalbeds as deep as 1,145 ft around borehole TW-5 in the Blue Creek Coalbed (Figure 6), but it was identifiable only as paint coatings, as no sand was used in the treatment (Lambert and others, 1980; Mahoney and others, 1981). The deepest stimulation with a sand-filled horizontal fracture was 1,093 ft in the Blue Creek Coalbed in borehole TW (Lambert and Trevits, 1978). In comparison, no horizontal fractures were identified in either of the two deepest mined-

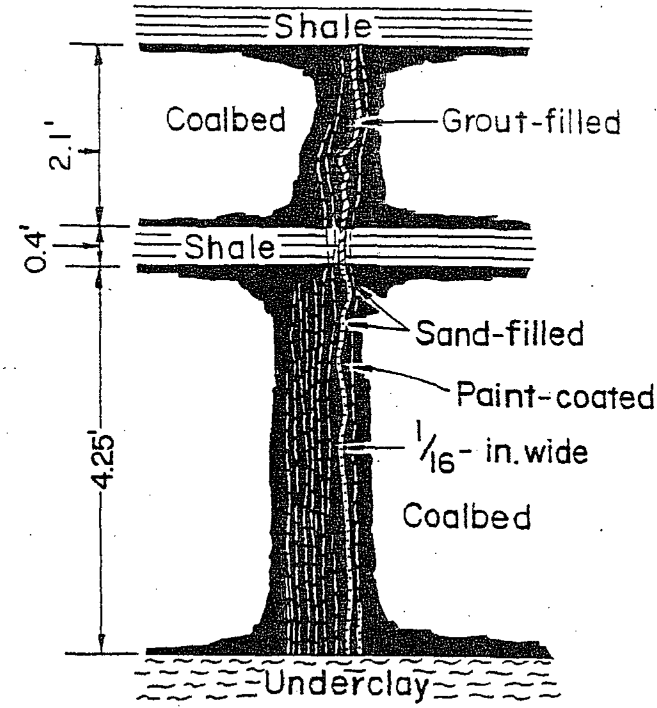

Figure 7. Cross-section of vertical fractures at location 25 on southeastern coal rib near borehole RP-1, Upper Freeport Coalbed, Lucerne No. 6 mine, Indiana County, Pennsylvania.

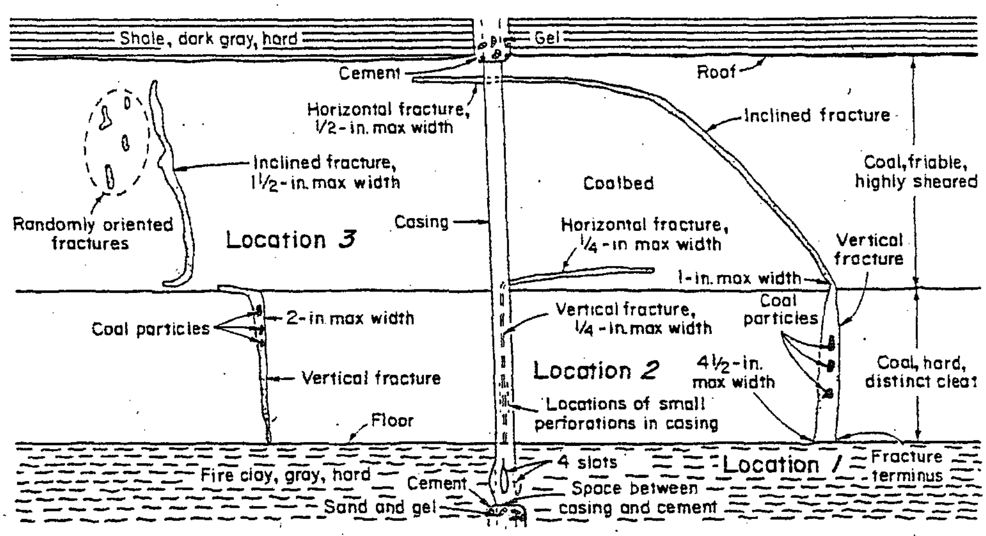

Figure 8. Cross-section of coal face at borehole TW-2, showing orientations and characteristics of fractures in the Blue Creek Coalbed, Oak Grove mine, Jefferson County, Alabama.

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through stimulations—Blue Creek Coalbed at 1,384 ft in borehole DHM-5 and at 1,239 ft in borehole DHM-6 (Boyer and Stubbs, 1983). Most likely, other horizontal fractures (or fluid pathways) might have been detected, especially in the shallow coalbeds, if fluorescent paint had been added to more treatments.

Horizontal fractures were most commonly observed at the interfaces between coalbeds and the roof rock, but some also were found along other distinct interfaces such as shale partings, shaly or hard, dense bands in the coalbed, or the bottoms or tops of rider coals in the immediate roof rock. Although generally erratic (in part because of difficulty in mapping their entire extent), the distribution of sand and paint on horizontal surfaces in two boreholes, RP-2 and RP-3, suggests some correlation between cleat orientation and the axes of horizontal lobes of paint (Figures 9 and 10). At borehole TW-5 the horizontal (and vertical) fractures covered a generally elliptical area whose long axis paralleled the face cleat orientation (Figure 6).

Multiple horizontal fractures on different planes have been observed in several cases. Although usually thin (< 1/2 in.), they vary considerably in width over short distances and may be discontinuous along an exposed rib (Figure 11). Sand-filled horizontal fractures were generally widest near the wellbore (maximum 1 in.). Their maximum observed lateral extents ranged from 200 ft in the Upper Freeport Coalbed at borehole RP-3 (Figure 10) to 250 ft in the Jawbone Coalbed at borehole DG-1A (Lambert and others, 1980). Maximum lateral extents of paint-coated horizontal fractures varied from 230 ft in the Blue Creek Coalbed at borehole TW-5 (Figure 6) to 200 ft and 265 ft in the Upper Freeport Coalbed at boreholes RP-2 and 3 (Figures 9 and 10).

Roof Penetration and Stability

Penetration by fluids and/or sand proppant into strata directly overlying the main coal bench has been observed in

Figure 9. Horizontal extent of indicator paints on mine roof around boreholes RP-1, RP-2, and RP-3, Lucerne No. 6 mine, Indiana County, Pennsylvania.

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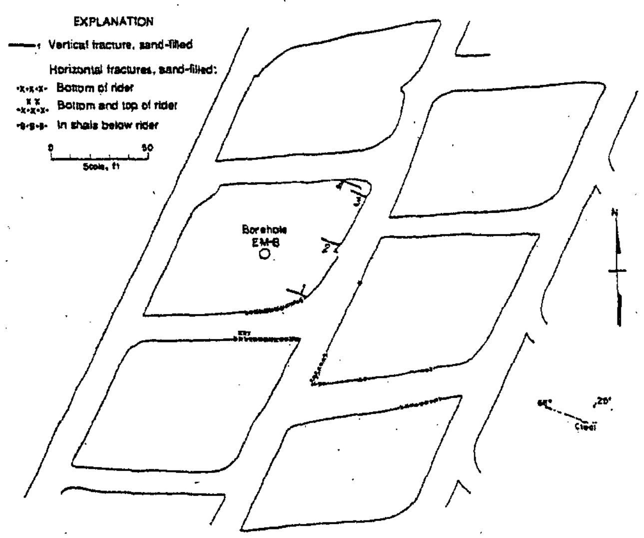
Figure 10. Horizontal extent of indicator paints and sand on top of shale parting around boreholes RP-1, RP-2, and RP-3, Lucerne No. 6 mine, Indiana County, Pennsylvania.



nearly half the treatments intercepted. In addressing the significance of roof penetration, it is necessary to point out that roof penetration does not necessarily equate to roof damage or adverse effects on mining. In government-sponsored treatments, no roof falls have occurred as a result of penetration of stimulation fluids into roof strata. Lambert and others (1980) 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 5.5 ft above had been stimulated and where mine management had observed "roof movement" along a nearby rib. According to Lambert and others, the area was mined through "without experiencing any roof fall during mining operations."

Figure 11. Locations of vertical and horizontal fractures around borehole EM-8, Pittsburgh Coalbed, Emerald mine, Greene County, Pennsylvania.

Except for the Blue Creek Coalbed in the Black Warrior basin, most of the penetrations of strata above the main coal bench have been fairly limited in vertical and/or horizontal extent. In several cases strata penetrations above the Blue Creek were observed 100 ft or more from the boreholes. Although not conclusively known, the reason for these more extensive roof penetrations may relate to the area's complex structural history. Recent in situ state-of-stress (ISSOS) tests conducted by GRI and USX Corp. at the Rock Creek site near the Oak Grove Mine indicated lower in situ stresses in the rocks surrounding the Mary Lee/Blue Creek coals than measured in the coals themselves (Popovich, 1985). Without a stress barrier or other mechanical property barrier under these conditions, upward fracture breakout most likely will result. Two such breakouts occurred above the Mary Lee and Blue Creek coals during ISSOS testing near the Oak Grove Mine (Popovich, 1985). The presence of naturally occurring roof joints combined with lower or similar in situ stresses above the coal probably influenced the extent of roof penetration at the mine.

In several cases the strata penetrated above coalbeds have been weak, thin shales below rider coals, and the fractures have been contained within strata that generally were mined along with the main bench of coal throughout the mine to prevent them from deteriorating and later falling (Figure 12).

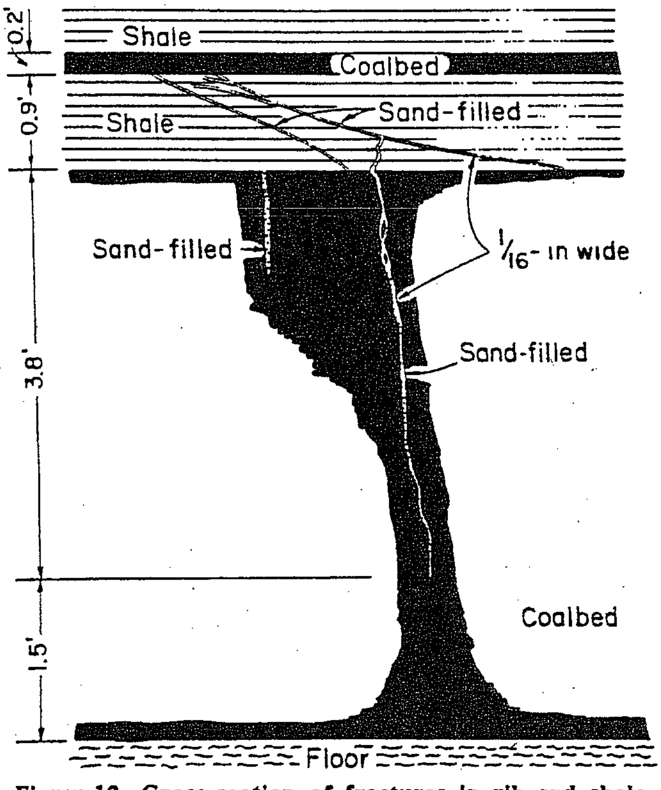


Figure 12. Cross-section of fractures in rib and shale parting at location 1 near borehole EM-8, Pittsburgh Coalbed, Emerald mine, Greene County, Pennsylvania.

Although these penetrations should not actually be considered "roof" penetrations, they are included as such in Table 2.

Reluctance to accept the use of stimulated vertical boreholes for coalbed degasification prior to mining may stem from use of the terms *fracture*, *fracturing*, and *breakdown*, which perhaps suggest a catastrophic breakup of the treated strata. Evidence from direct underground observations and data from many treatment records (including those from boreholes not mined through) suggest that *new* fractures seldom are created; rather, naturally occurring planes of weakness (cleat, joints, or bed boundaries) are entered by the fracturing fluids and opened to varying degrees. In most cases the penetration of strata overlying a main coal bench has been attributed to fluid invasion of preexisting joints, as evidenced by the general regularity of joint character and orientation throughout a mine.

SUMMARY

The type of stimulation fluid influences to some degree the character of induced hydraulic fractures, as do such other factors as treatment volume, injection rate, and depth and physical character of the coalbed. Large-volume treatments tend to result in more observable fractures, as was the case in the three progressively larger treatments in the Upper Freeport Coalbed in boreholes RP-1, RP-2, and RP-3 (Figure 5). Two of the largest volume treatments, boreholes TW-5 (Figure 6) and DHM-6 (Figure 4), also created some of the most extensive networks of fractures.

The physical properties of the coalbed apparently have some influence on fracture propagation. Many vertical fractures in the Blue Creek Coalbed were present only in its more friable upper part. Sand-filled fractures at borehole TW-2 began vertically in "hard" coal at the bottom of the Blue Creek but inclined and became horizontal at or near the interface with the upper friable section (Figure 8). The distinct shale parting near the top of the Upper Freeport Coalbed in boreholes RP-1, RP-2, and RP-3 in some cases acted as a barrier to upward fracture growth, as seen with most paint-coated fractures (Figure 7). More commonly, however, vertical fractures penetrated the shale parting, then became horizontal at the interface with the base of the upper coal bench (Figure 13). A distinct shaly band in the Pittsburgh Coalbed at borehole EM-8 generally was penetrated by vertical fractures, which continued vertically above it (Figure 14), except in one instance where the fracture became horizontal (Figure 15). Small horizontal offsets in vertical propagation also were commonly observed as the fractures encountered different layers or bedding planes within the coalbed (Figure 14). These offsets occasionally gave the vertical fracture an inclined or sinuous appearance. Although the coalbed's physical properties appear to influence the character of induced fractures, that influence is variable and cannot be considered predictable.

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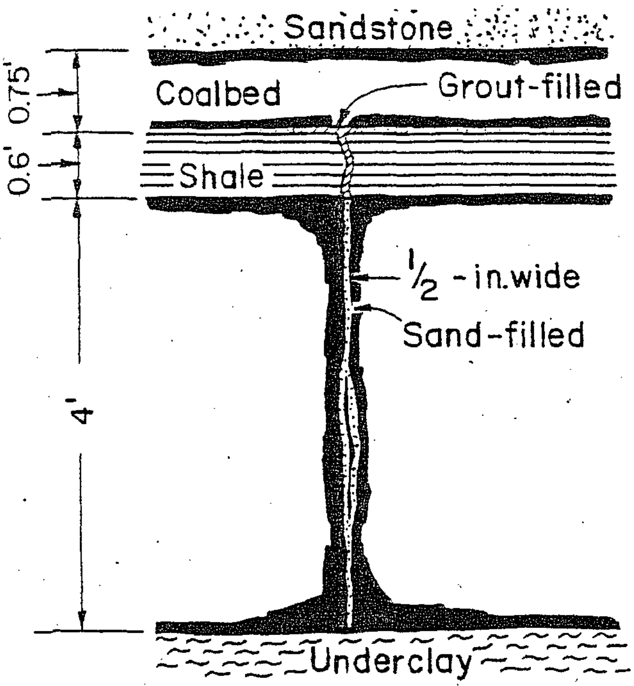

Figure 13. Cross-section of fractures in rib and shale parting at location 7 on the northwest rib near borehole RP-2, Upper Freeport Coalbed, Lucerne No. 6 mine, Indiana County, Pennsylvania. Modified from Murrie and others (1984).

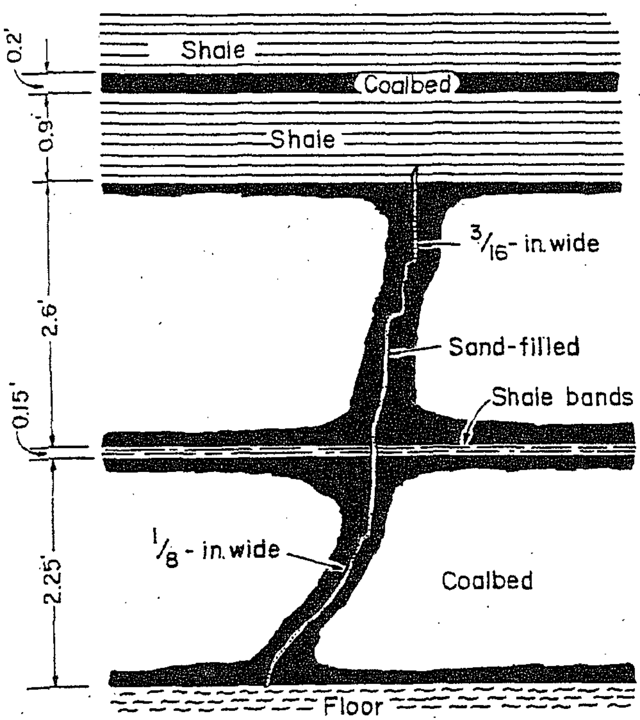

Figure 14. Cross-section of fracture in rib and shale partings at location 4 near borehole EM-8, Pittsburgh Coalbed, Emerald mine, Greene County, Pennsylvania.

It is impossible to guarantee that a coalbed stimulation treatment will not adversely affect mining in some way. However, the evidence observed underground and the experience gained to date suggest that the probability of additional hazard to the mine environment is minimal. Nevertheless, prestimulation strata-characterization tests, careful treatment design, and controlled implementation (primarily injection rates and therefore treatment pressure) are strongly recommended to minimize the potential for hydraulic fracture-induced roof and seam instability.

ACKNOWLEDGMENT

The author wishes to acknowledge Mr. Stephen W. Lambert of Taurus Exploration Inc., for his valuable information on underground fracture observations in the Alabama mines.

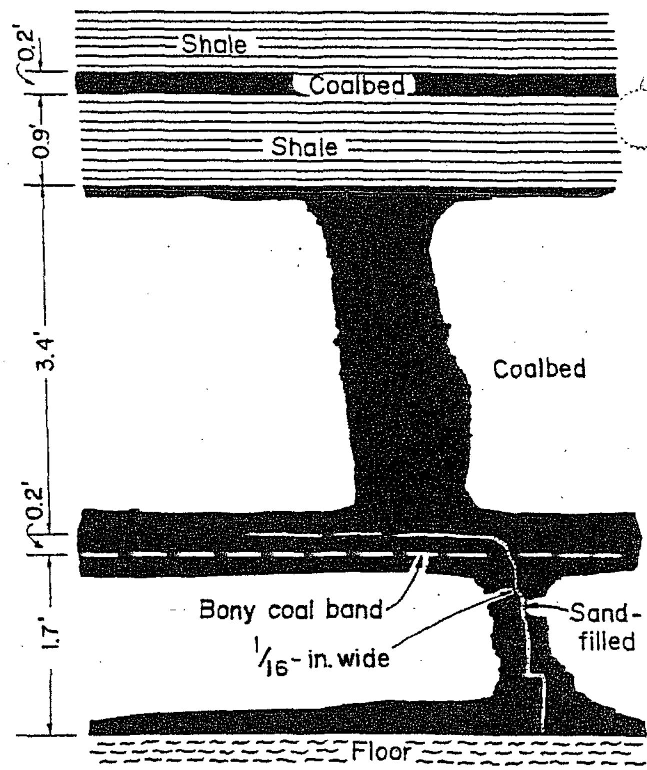

Figure 15. Cross-section of fracture in rib at location 2 near borehole EM-8, Pittsburgh Coalbed, Emerald mine, Greene County, Pennsylvania.

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