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Loading Characteristics of Pillars in Multiple-Seam Mining Operations

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	psi	pound per square inch
ft^2	square foot	psig	pound per square inch, gauge
in	inch	yr	year
pct	percent		

LOADING CHARACTERISTICS OF PILLARS IN MULTIPLE-SEAM MINING OPERATIONS

By G. J. Chekan[1] and R. J. Matetic[1]

ABSTRACT

The Bureau of Mines, in an effort to improve resource conservation, mine planning and development, is currently investigating the loading behavior of pillars in multiple-seam developments. The simultaneous mining of two or more coalbeds may cause instability between room-and-pillar operations resulting in an interaction known as pillar load transfer. Although pillars may be adequately designed for single-seam mining, the development of a second seam may complicate loading conditions in both operations. If pillars are not adequately designed to contend with this load transfer, failure of the mine structure may result.

To improve multiple-seam development and pillar design, the Bureau studied the loading characteristics of pillars in three separate multiple-seam operations. In all three cases, instrumented pillars recorded increasing pressure after development of the second seam. Increases in the average pillar pressure ranged from 7 to 110 pct over predicted overburden loads. An analysis of pillar loading before and after second-seam mining indicates that the ratio of overburden to innerburden thickness is a critical factor influencing load transfer. Based on this relationship, safety factors for case study pillars are calculated and alternative design considerations are discussed.

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INTRODUCTION

The transfer of load between pillars in multiple-seam operations has been documented in various field studies. The parameters that control the interaction can be classified into two categories: (1) fixed parameters, which are dependent upon the geologic environment and include overburden, innerburden thickness and physical characteristics, seam height, coal strength, and in situ stress fields; and (2) design parameters, which are dependent upon engineering design and include pillar size, entry span, seam sequencing, mining method, and mining height. Comparative studies which relate these two sets of parameters have provided insight into delineating principal factors that control the magnitude and distance of load transfer. Researchers have developed empirical relationships that investigated the fixed parameters, independent of design. These relationships indicate that depth, innerburden thickness, layering, and physical characteristics all have an effect on the magnitude of load transfer. One relationship suggests that interactive distance between room-and-pillar operations may be limited to 110 ft regardless of depth (1-2).[2] Photoelastic and numerical models, which have been developed to study engineering design, indicate that pillar size is a critical factor influencing interactive distance. Interactive distance is controlled by the least width of the pillar, and rectangular pillars will generally transfer less load a shorter distance as compared to a square pillar of equal load-carrying capacity (2-3). Other factors, such as seam height, coal characteristics, in situ stresses, seam sequencing, and mining method, all contribute to the transfer mechanism to some degree, but their importance varies depending on site specifics.

Although these studies provide considerable understanding to the problem, few investigations involve the actual underground instrumentation and monitoring of pillars during multiple-seam development. To further study load transfer between pillars in multiple-seam operations, the Bureau of Mines collected various geomechanical information at three separate mine sites. Fixed and design parameters varied, but a comparison of the sites shows the following:

1. All three sites were simultaneous room-and-pillar operations (upper and lower mines). Pillar superpositioning was practiced at two sites; the other used random pillar arrangements.

2. Pillars had similar load-carrying capacities. At two sites pillars were 45 by 60 ft, and they were 55 by 55 ft at the third.

3. Percent extraction was similar at all six mines, ranging from 0.45 to 0.48.

4. Innerburden was less than 110 ft at all three sites.

The Bureau conducted these studies to develop a better understanding of load transfer between pillars in simultaneous mining operations. Eventually, this knowledge will lead to improvements in the planning and development of multiple seams.

[2]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

COMPARISON OF MINE SITES

FIXED AND DESIGN PARAMETERS

Tables 1 and 2 compare the fixed and design parameters for the three sites. Methods for calculating σ_1, the in situ strength of coal, are given in the appendix.

INSTRUMENTATION OF PILLARS

Pillar pressures at all three sites were monitored using a simple and inexpensive instrument known as the borehole platened flatjack (BPF) (4). The instrument was developed for measuring mining-induced pressure changes in coal measure strata (fig. 1). It consists of a copper flatjack or bladder positioned between two aluminum platens. The instrument is installed in a 2-in-diam borehole in the pillar, and the flatjack is inflated with hydraulic oil to a predetermined setting pressure. BPF's can be oriented in the borehole to measure pressure changes in any direction. At all three sites, the BPF's were oriented to measure vertical increases in pillar pressure.

TABLE 1. - Comparison of fixed parameters

Fixed parameter	Case 1	Case 2	Case 3
LOCATION			
County	Indiana	Saline	Raleigh.
State	Pennsylvania	Illinois	West Virginia.
COAL CHARACTERISTICS			
Upper coalbed	Upper Freeport	Herrin No. 6	Peerless.
Thickness...in	42	72	72.
Strength, psi:[1]			
Cubical specimen (σ_c)	ND	ND	1,870.
In situ coal (σ_1)	ND	ND	440.
Lower coalbed	Lower Freeport	Springfield No. 5	No. 2 Gas.
Thickness...in	54	92	48.
Strength, psi:[1]			
Cubical specimen (σ_c)	2,360	2,690	ND.
In situ coal (σ_1)	556	634	ND.
OVERBURDEN			
Depth to upper coalbed...ft	345	445	960.
Composition	Interbedded shale and sandstone.	Interbedded shale	Sandstone and interbedded shales.
INNERBURDEN			
Thickness...ft	65	105	40.
Composition	Interbedded shales.	Interbedded shale	Sandstone and shale.

ND Not determined. [1]See appendix.

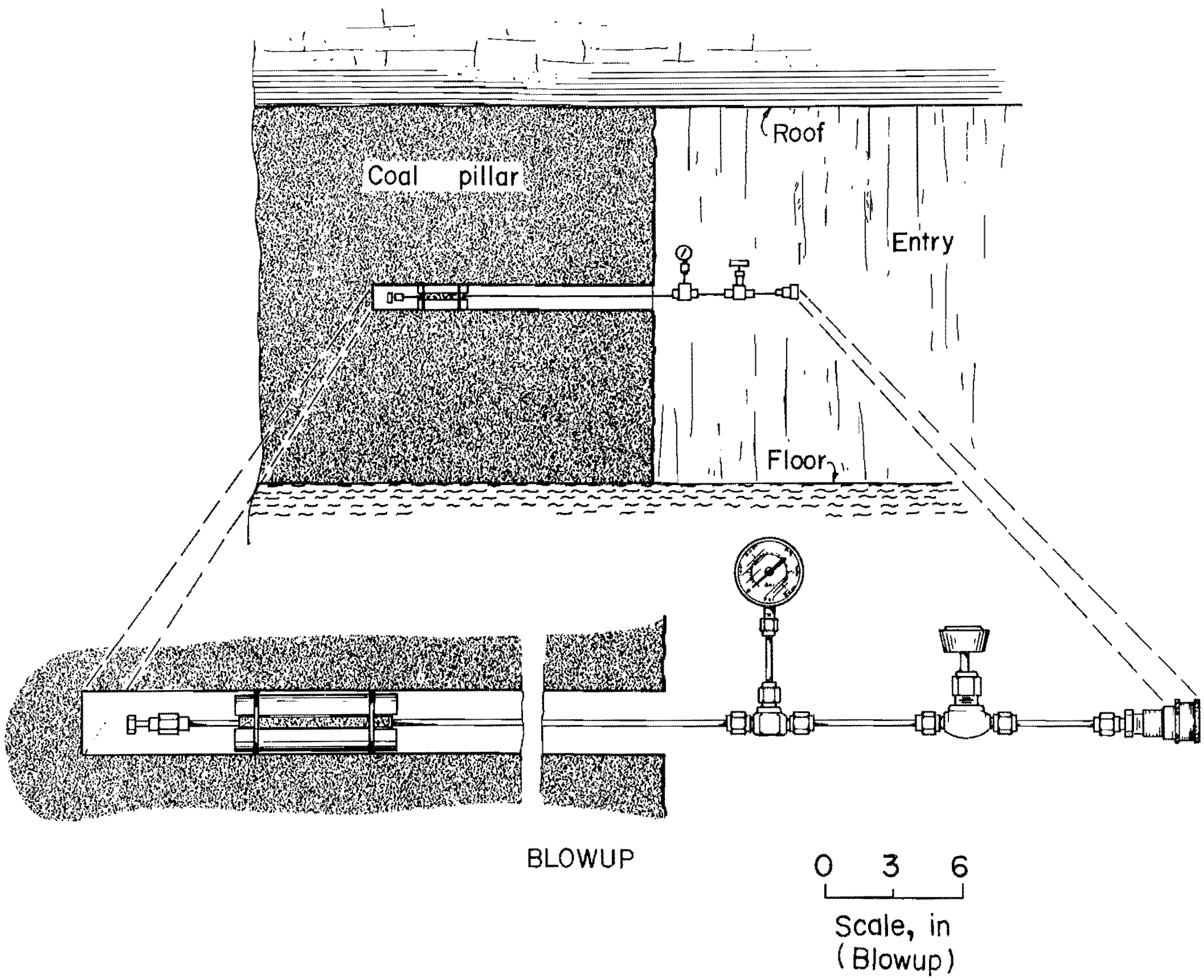

FIGURE 1.--Schematic of borehole platened flatjack.

Setting pressure for the BPF is determined by using a commonly used method to calculate the pressure in the pillar due to the weight of the overburden. The BPF is then set in the borehole to match this value, which is usually rounded to the nearest 100 psi. BPF setting pressure usually drops 200 to 300 psi in the first few days after installation as the instrument reaches equilibrium with the host strata. Calibration tests conducted on the BPF's suggest that the relationship between actual strata pressure and BPF pressure can be represented by the curve in figure 2. These tests indicate that flatjack sensitivity or K-factor is directly related to the setting pressure of the instrument. Therefore, increases in pillar pressure can be approximated by using the tributary area method in conjunction with the equilibrium pressure of the BPF, the K-factor, and the peak pressure recorded from the BPF after second mining. The equations for determining this value are as follows:

$$TAM = 1.1\ (d) \left(\frac{1}{1 - R} \right), \qquad (1)$$

where TAM = tributary area method, psi,

1.1 = constant, psi/ft of overburden,

TABLE 2. - Comparison of design parameters

Design parameter	Case 1	Case 2	Case 3
Mining method:			
Upper mine.................	Room-and-pillar..	Room-and-pillar..	Room-and-pillar.
Lower mine.................	...do...........	...do...........	Do.
Mining height, in:			
Upper mine.................	42..............	72..............	72.
Lower mine.................	54..............	92..............	48.
Pillar superpositioning......	No..............	Yes.............	Yes.
Seam sequencing:			
Upper mine.................	2d..............	2d..............	1st.
Lower mine.................	1st.............	1st.............	2d.
Pillar dimension (W × L), ft:			
Upper mine.................	40 by 60.........	55 by 55.........	45 by 60.
Lower mine.................	45 by 60.........	55 by 55.........	45 by 60.
Entry width, ft:			
Upper mine.................	18..............	20..............	18.
Lower mine.................	20..............	20..............	18.
Percent extraction (R), pct:			
Upper mine.................	0.47............	0.46............	0.45.
Lower mine.................	0.48............	0.46............	0.45.

d = depth, ft,

and R = percent extraction;

$$P_2 = TAM + (BPF_P - BPF_E)\left(\frac{1}{K}\right), \quad (2)$$

where P_2 = pillar pressure after second-seam mining, psi,

TAM = tributary area method, psi,

BPF_P = peak pressure recorded from BPF after second-seam mining, psi,

BPF_E = equilibrium pressure of BPF after installation, psi,

and K = constant factor, dependent on BPF setting pressure estimated from figure 2.

Case 1

This simultaneous mining operation is located in Indiana County, PA, and the operator is working both the Upper and Lower Freeport Coalbeds (5). A stratigraphic column representative of the study area is shown in figure 3. The innerburden averages 65 ft in thickness and consists predominantly of innerbedded shale. The overburden above the Upper Freeport Coalbed (upper coalbed) ranges from 330 to 430 ft and is approximately 345 ft at the study site.

Figure 4 shows the location of six BPF's in three selected pillars of the lower mine. BPF's were installed approximately 65 days before development was directly superjacent in the upper mine.

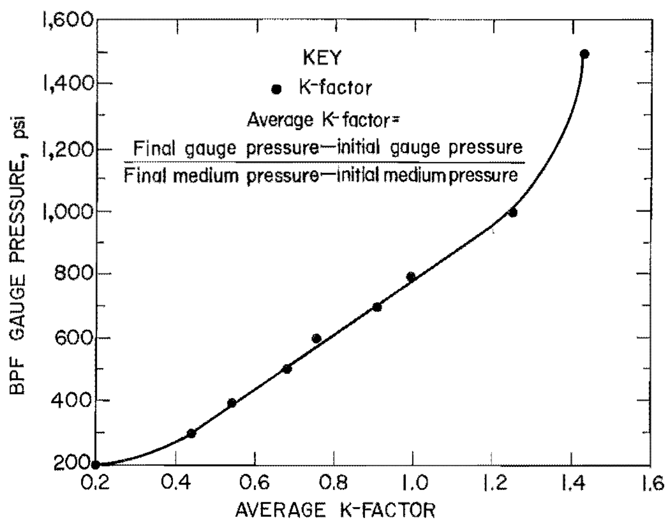

FIGURE 2.--K-factor curve for borehole platened flatjack.

TABLE 3. - Increase in pillar load (ΔP) after second-seam mining for case 1

(Setting pressure, 900 psig; K-factor, 1.12; TAM, 870 psi)

BPF	Installation depth, ft	BPF_E, psig	BPF_P, psig	P_2, psi	ΔP,[1] psi	BPF	Installation depth, ft	BPF_E, psig	BPF_P, psig	P_2, psi	ΔP,[1] psi
1......	22	825	925	960	90	5......	22	800	900	960	90
2......	10	825	900	935	65	6......	10	800	850	915	45
3......	23	800	900	960	90	Av...	NAp	NAp	NAp	NAp	65
4......	10	800	825	895	25						

NAp Not applicable. [1]$\Delta P = P_2 - TAM$.

NOTE.--K-factor determined from figure 2.

At this site, pillar superpositioning was not practiced as figure 5, an overlay of the two mines after development, shows.

Table 3 lists the values of the variables in equations 1 and 2 for calculating P_2.

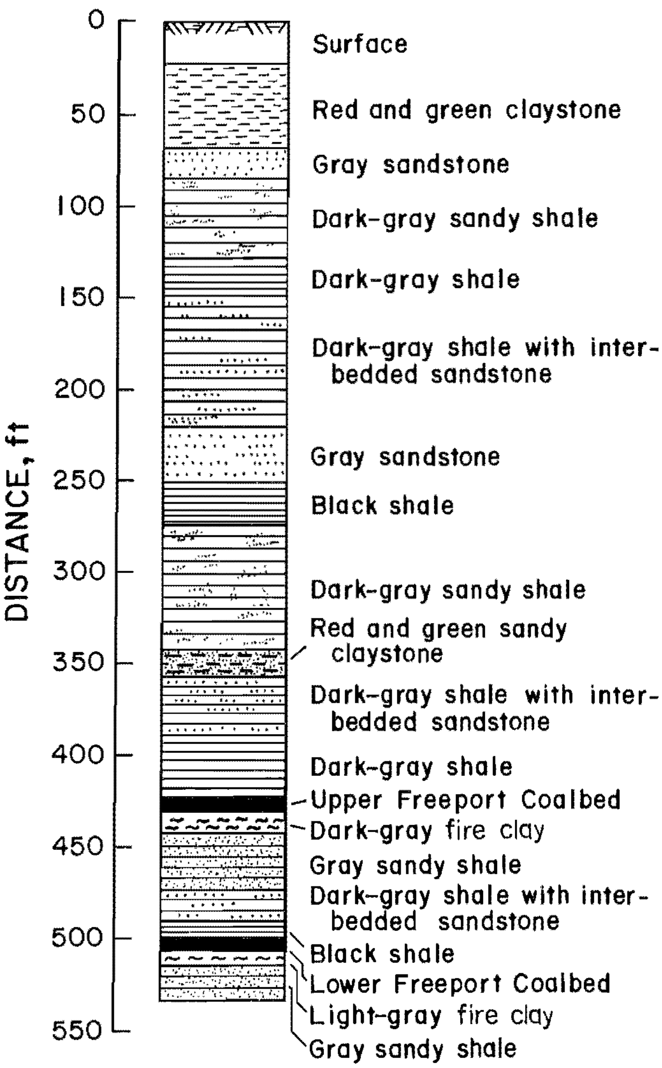

FIGURE 3.--Stratigraphic column for case 1.

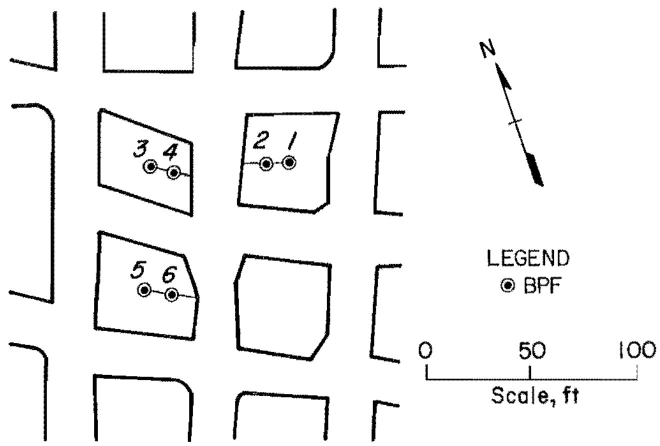

FIGURE 4.--Location of BPF's in pillars of lower mine for case 1.

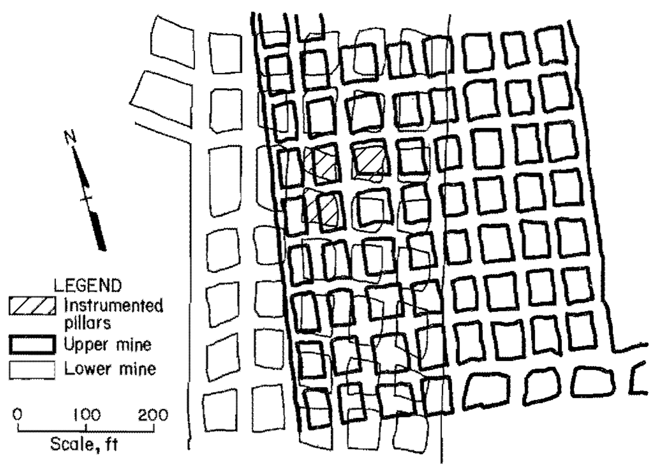

FIGURE 5.--Overlay of two mines in study area for case 1.

Case 2

This simultaneous mining operation is located in Saline County, IL, and the operator is working the Herrin Coalbed No. 6 and the Springfield Coalbed No. 5. A stratigraphic column representative of the study area is shown in figure 6. The innerburden is approximately 105 ft thick consisting predominantly of shale with a narrow sandstone unit 7 ft thick. The overburden above the Herrin Coalbed No. 6 is approximately 445 ft at the study area. It consists of interbedded shale and sandstone with some narrow limestone units. Figure 7 shows the location of the 18 BPF's in nine selected pillars of the lower mine. BPF's were installed approximately 20 days before pillar development was directly superjacent in the upper mine. Pillar superpositioning was practiced at this site as figure 8, an overlay of the two mines after development, shows. Table 4 lists the values of the variables in equations 1 and 2 for calculating P_2.

TABLE 4. - Increase in pillar load (ΔP) after second-seam mining for case 2

(BPF setting pressure, 1,000 psig; K-factor, 1.24; TAM, 1,120 psi)

BPF	Installation depth, ft	BPF_E, psig	BPF_P, psig	P_2, psi	ΔP,[1] psi
1....	25	900	1,000	1,200	80
2....	10	900	1,000	1,200	80
3....	25	825	875	1,160	40
4....	10	900	950	1,160	40
5....	27	925	975	1,160	40
6....	8	875	975	1,200	80
7....	27	900	900	1,120	0
8....	12	550	600	1,160	40
9....	27	875	900	1,140	20
10...	12	900	975	1,180	60
11...	20	900	925	1,140	20
12...	12	925	950	1,140	20
13...	20	825	850	1,140	20
14...	12	825	1,675	1,820	700
15...	24	725	750	1,140	20
16...	11	900	900	1,120	0
17...	27	850	850	1,120	0
18...	11	775	900	1,225	105
Av.	NAp	NAp	NAp	NAp	75

NAp Not applicable. [1]ΔP = P_2 − TAM.

NOTE.--K-factor determined from figure 2.

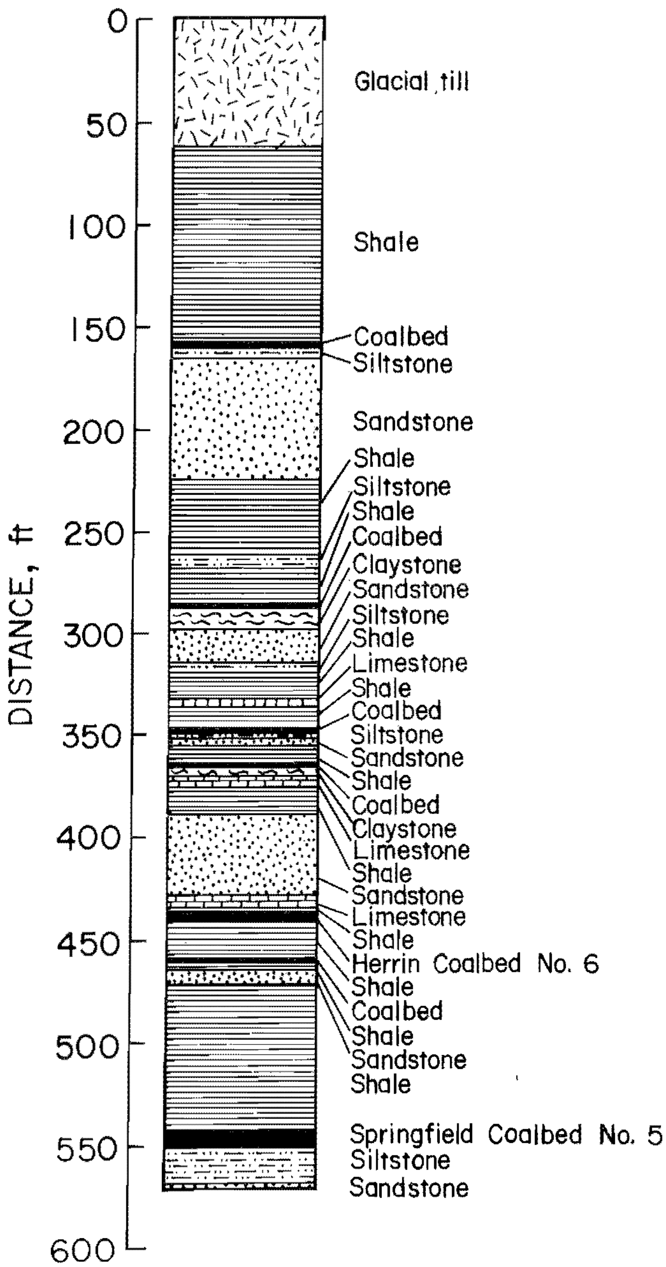

FIGURE 6.--Stratigraphic column for case 2.

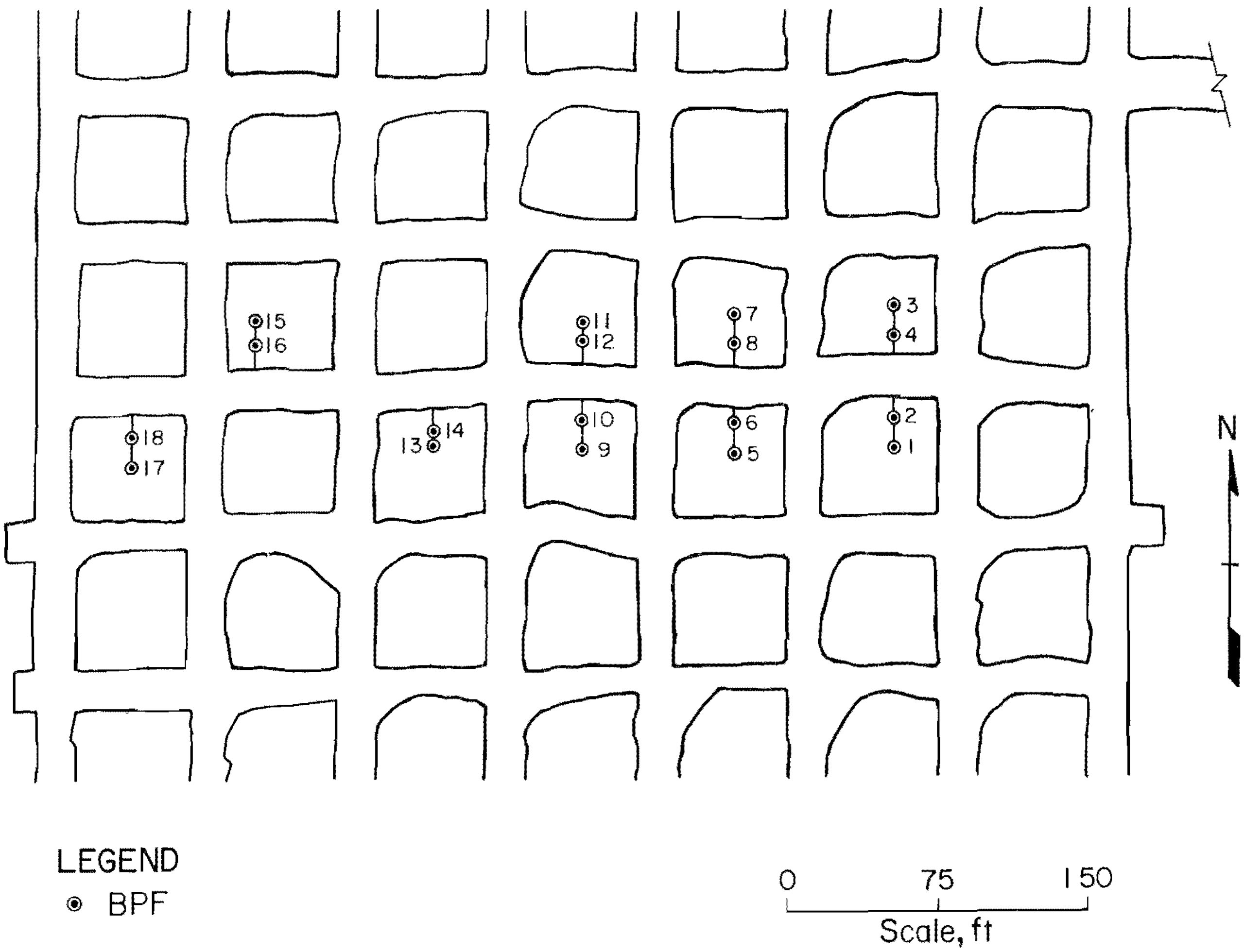

FIGURE 7.--Location of BPF's in pillars of lower mine for case 2.

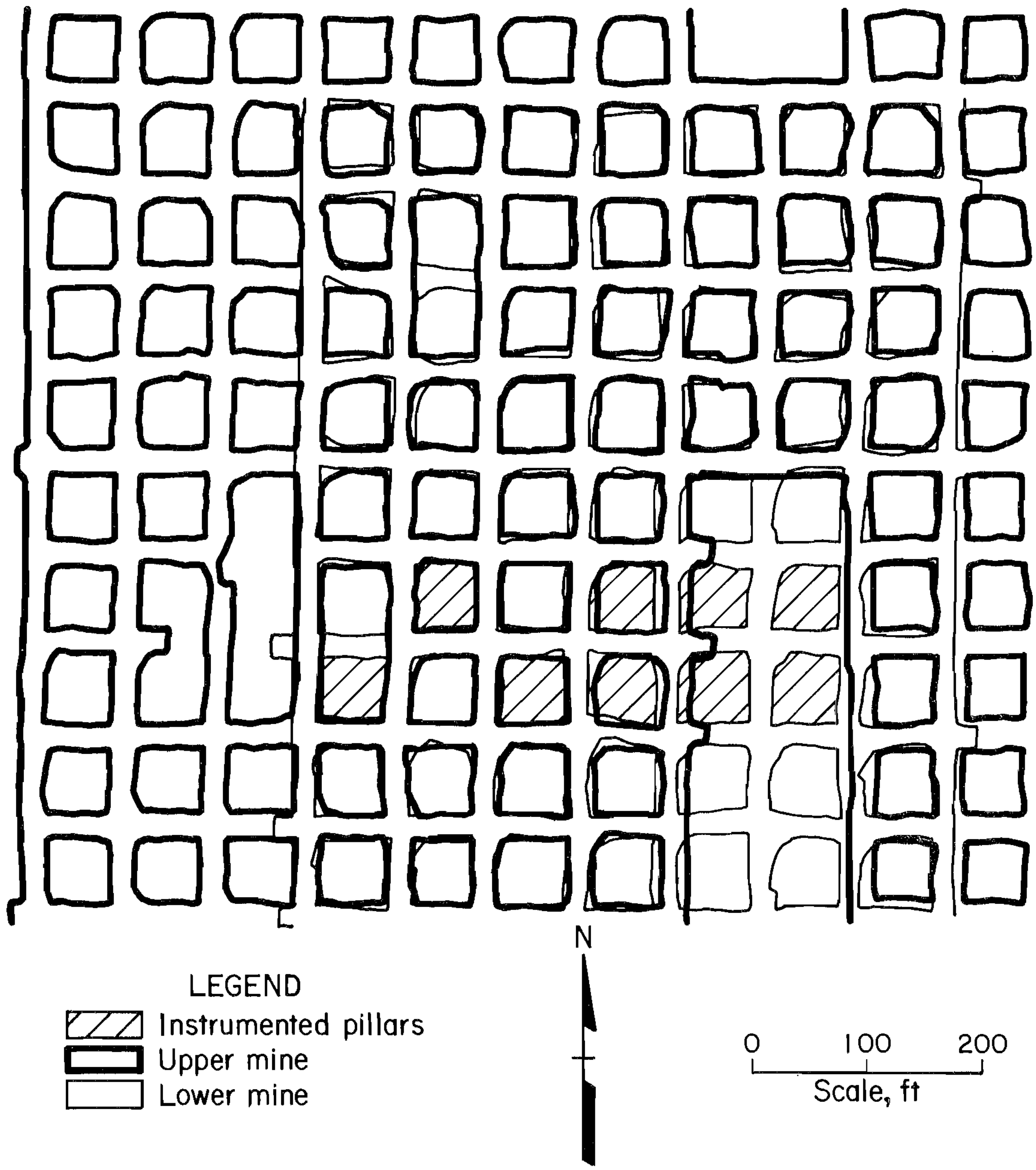

FIGURE 8.--Overlay of two mines in study area for case 2.

Case 3

This simultaneous mining operation is located in Raleigh County, WV, and the operator is working the Peerless and No. 2 Gas Coalbeds (6). A generalized stratigraphic column representative of the entire mine is shown in figure 9. The innerburden is approximately 40 ft thick consisting predominantly of sandstone with some interbedded shale units. The overburden above the Peerless Coalbed is approximately 960 ft at the study area and consists of sandstone with some interbedded shale units. Figure 10 shows the location of four BPF's in two selected pillars of the upper mine. Pillar superpositioning was practiced at this site as figure 11 shows an overlay of the two mines after development. BPF's were installed after problems were first noticed, approximately 2 yr after the development of both coalbeds. Ground problems, which included excessive pillar loading, spalling, and floor heaving, occurred first in the upper mine, but in several months gradually affected both operations. Table 5 lists the values of the variables in equations 1 and 2 for calculating P_2.

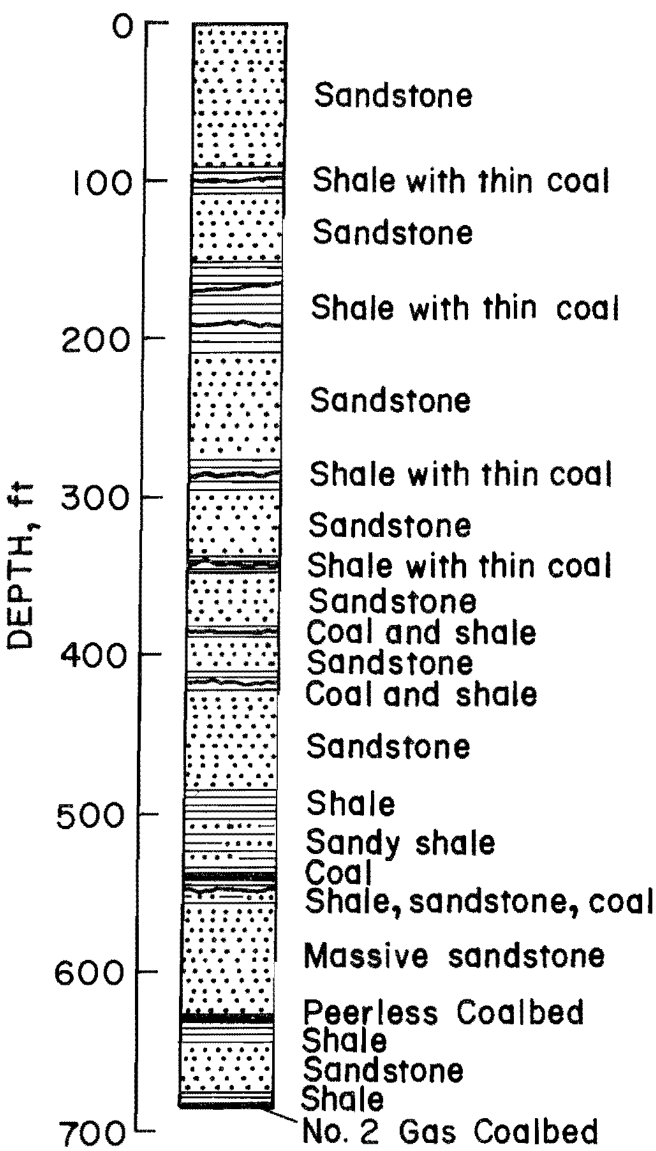

FIGURE 9.--Stratigraphic column for case 3.

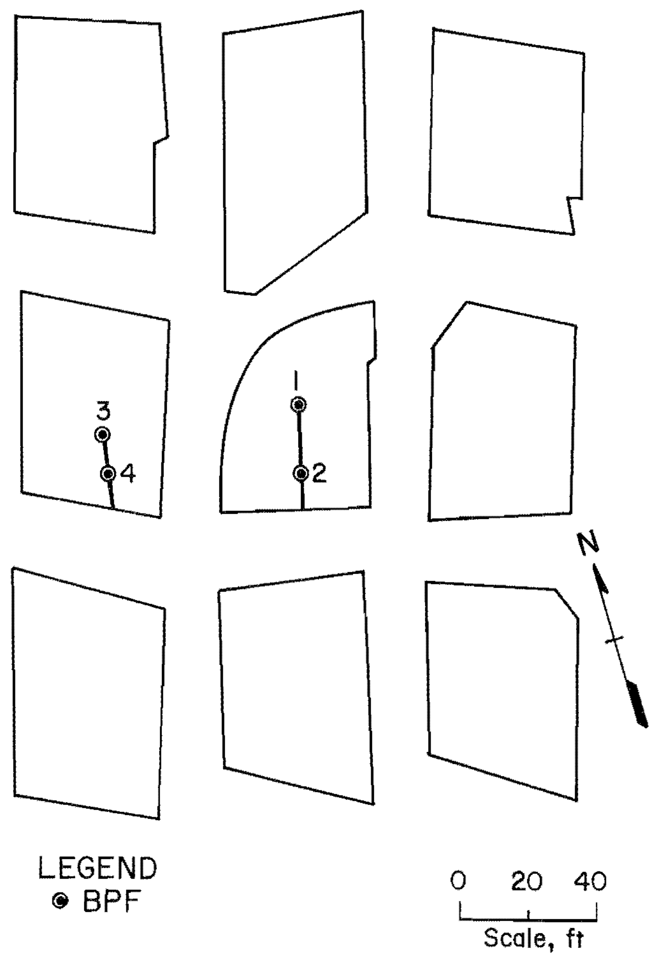

FIGURE 10.--Location of BPF's in pillars of upper mine for case 3.

TABLE 5. - Increase in pillar load (ΔP) after second-seam mining for case 3

(TAM, 1,920 psi)

BPF	Installation depth, ft	Setting pressure, psig	K-factor[2]	BPF_E, psig	BPF_P, psig	P_2, psi	ΔP,[1] psi
1......	25	1,100	1.30	1,100	8,100	7,300	5,380
2......	12	1,225	1.36	900	950	1,960	40
3......	22	1,200	1.34	1,200	5,100	4,830	2,910
4......	10	1,275	1.38	1,200	1,250	1,960	40
Av...	NAp	NAp	NAp	NAp	NAp	NAp	2,095

NAp Not applicable. [1]$\Delta P = P_2 - TAM$. [2]Determined from figure 2.

PILLAR LOAD TRANSFER CHARACTERISTICS

Hypotheses concerning pillar loading (7) have divided the pillar into two distinct zones; the core and the yield zone. The core is the zone in the pillar center that behaves elastically and is confined by the yield zone which surrounds it.

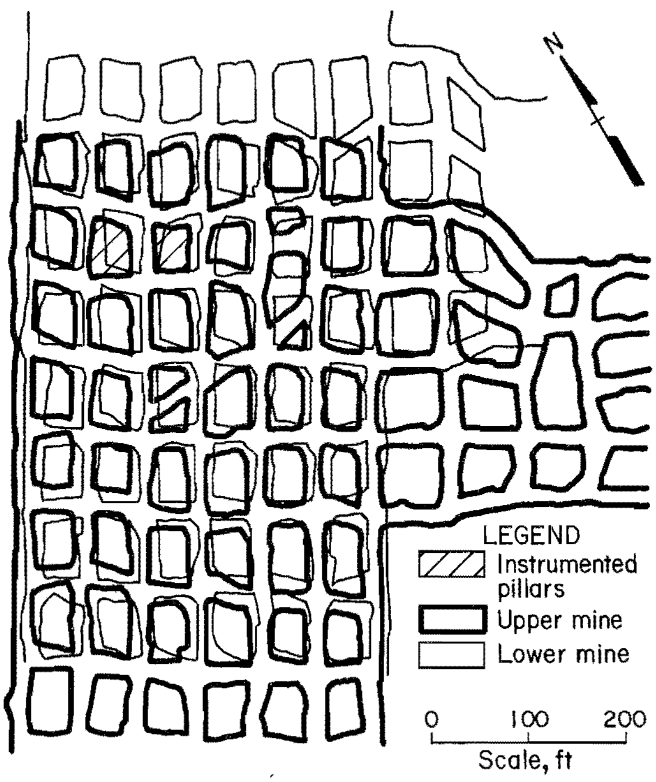

FIGURE 11.--Overlay of two mines in study area for case 3.

Figure 12 shows three basic loading characteristics for pillars. Figure 12*A* shows a peak-trough-loaded pillar where the highest pressure occurs towards the pillar yield zone. Photoelastic models (2) have shown that pillars loaded in this manner are a stable design and are unlikely to transfer load to underlying or overlying operations. Several pillars in case 2 displayed this type of loading behavior after development of the second seam, and underground observation showed the study area to be relatively stable. A uniform loading (fig. 12*B*) rarely occurs in actual underground conditions, although it is used frequently in theoretical design. A pillar that loads in this manner is more likely to transfer load, but is also considered a stable design. Pillars in case 1 displayed this type of loading behavior. A pillar that displays a peak loading (fig. 12*C*), where the highest pressure occurs towards the pillar core, is considered an unstable design and highly likely to transfer load. In engineering practice, the upper limit of average stress in the pillar core is estimated at four times the overburden load (7). The pillars in case 3 displayed this loading characteristic. Visual observation of the study area showed the mine structure to be very unstable as floor heaving and pillar spalling were the major ground problems.

Additionally, a pillar may display a peak-trough loading, but gradually decay to a peak loading. This is caused by a time-dependent failure of the yield zone as the load is gradually transferred to the pillar core. This process is a function of the pressure, pillar dimensions, and the strength of the coal and surrounding strata. This time-dependent failure correlates well with documented pillar load transfer case studies that show that ground problems do not develop immediately, but usually several months or years after both workings have been developed (1-2, 5-6).

PILLAR SAFETY FACTORS

Additional loads imposed on pillars resulting from the development of a second seam can cause instability in one or both operations. This is particularly true if pillars are not properly designed with adequate safety factors to contend with this load transfer. There are many methods available for calculating pillar strength and resulting safety factors. Research has shown (8) that pillar strength is characterized by two effects, the shape and size. The more commonly used pillar design formulas take these two factors into consideration. These design formulas account for the differences in the strength reduction between small-size specimens tested in the laboratory and full-size coal pillars mined in situ. From available pillar design methods the following four formulas are most applicable to room-and-pillar coal mines.

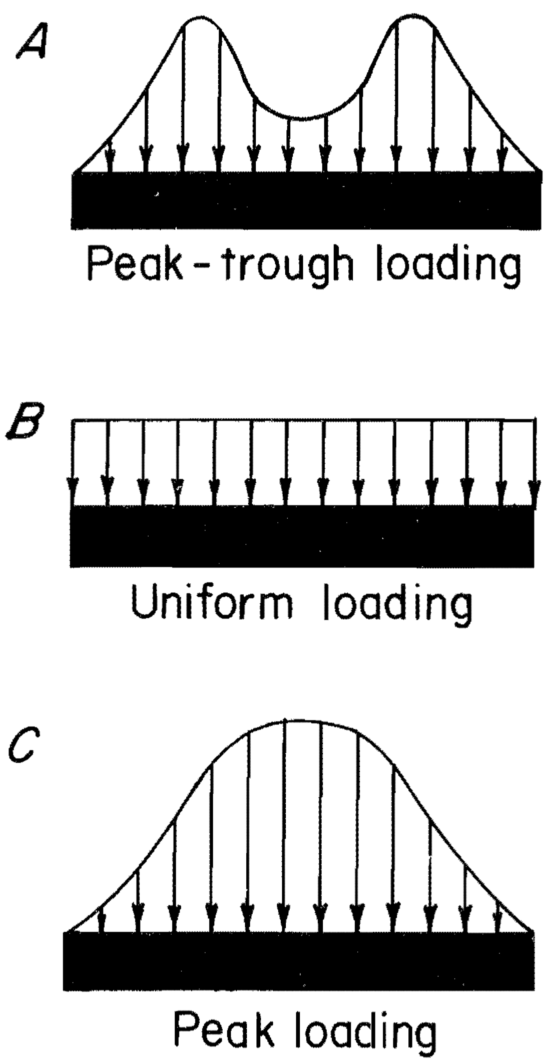

FIGURE 12.--Loading characteristics of pillars.

1. Obert-Duvall:

$$\sigma_p = \sigma_1\,(0.788 + 0.222\,w/h), \quad (3)$$

where σ_p = the pillar strength, psi,

σ_1 = in situ coal strength, psi (see appendix),

w = least width of pillar, in,

and h = height of pillar, in.

2. Holland-Bureau:

$$\sigma_p = \sigma_1\,(w/h)^{1/2}, \quad (4)$$

where σ_p = the pillar strength, psi,

σ_1 = in situ coal strength, psi (see appendix),

w = least width of pillar, in,

and h = height of pillar, in.

3. Holland-Gaddy:

$$\sigma_p = \sigma_{c/h}\,(D_w)^{1/2}, \quad (5)$$

where σ_p = strength of mine pillar, psi,

σ_c = cubical specimen strength, psi,

h = height of pillar, in,

D = side dimension of cubical specimen, in,

and w = least width of pillar, in.

4. Bieniawski-Pennsylvania State University:

$$\sigma_p = \sigma_1 (0.64 + 0.36 w/h), \quad (6)$$

where σ_p = strength of mine pillar, psi,

σ_1 = in situ coal strength, psi (see appendix),

w = least width of pillar, in,

and h = height of pillar, in.

These formulas can be used in conjunction with the TAM (which assumes the pillar to be gravity loaded only) to determine the pillar safety factors. Table 6 lists the safety factors before and after second-seam mining for these four formulas. This analysis is based on data obtained from instruments that detect stress changes in coal measure strata. The accuracy of these instruments, such as the BPF or vibrating-wire stressmeter, is uncertain. The unresolved problems are directed at the calibration of the instrument or the relation between recorded stress changes and the stress that is actually experienced in situ. Although the margin of error is debatable, such exercises are necessary to gain insight into the relationship between pillar loading and instrument behavior. Other studies (9-10) have attempted similar interpretations, and one positive aspect this research has shown is that these instruments function well as trend indicators, especially when coordinated with underground observation.

TABLE 6. - Safety factors for pillars

	Case 1	Case 2	Case 3
Estimated load on pillar using tributary area method (TAM)....................psi..	870	1,120	1,920
Average increase in pillar pressure after 2d-seam development.................psi..	65	75	2,095
Increase over TAM.....................pct..	7.5	6.7	109.4
Estimated load on pillar after 2d-seam mining..............................psi..	935	1,195	4,015
Overburden-innerburden ratio.............	5.3:1	4.2:1	24:1
Pillar strength (σ_p), psi:			
Obert-Duvall..........................	1,672	1,510	1,080
Holland-Bureau........................	1,758	1,698	1,205
Holland-Gaddy.........................	1,437	1,063	854
Bieniawski-PA State Univ................	2,357	2,043	1,470
Safety factor before 2d-seam development:			
Obert-Duvall..........................	1.92	1.34	0.56
Holland-Bureau........................	2.02	1.52	0.63
Holland-Gaddy.........................	1.65	0.95	0.44
Bieniawski-PA State Univ................	2.71	1.82	0.77
Safety factor after 2d-seam development:			
Obert-Duvall..........................	1.78	1.26	0.26
Holland-Bureau........................	1.88	1.42	0.30
Holland-Gaddy.........................	1.54	0.89	0.21
Bieniawski-PA State Univ................	2.52	1.71	0.37

Pillar strength and safety factors for this analysis were derived using the ultimate strength approach. This design method makes two assumptions: (1) pillar strength is related to the uniform, ultimate strength derived by scaling uniaxial strength values laboratory specimens; and (2) an average pillar stress or load exists across the pillar in situ. Recommended safety factors for pillars designed by this approach generally range between 1.5 and 2.2 (8). The Bieniawski-Pennsylvania State University formula gives the highest safety factors for all three cases. For cases 1 and 2, safety factors generally remained above 1.

Observations on ground conditions at these two sites showed that pillars experienced some slight rib spalling after second-seam development, but for the most part remained intact and very stable. The entries in the study areas also remained stable. Some slight floor heaving was evident at site 1 and some poor roof conditions existed at site 2, but this could be due to a regional stress field (11). The overburden-innerburden ratios at sites 1 and 2 were 5.3:1 and 4.2:1, respectively. Case 3 experienced the worst conditions of the three sites. Safety factors indicate that pillars were most likely underdesigned even before second-seam mining, but problems were not experienced until 2 yr after both operations were developed. The overburden-innerburden ratio at this site is 24:1.

Field studies (1) that relate room-and-pillar stability to depth and innerburden thickness, independent of pillar design, suggest that when innerburden-to-overburden ratio exceeds 8:1, an unstable condition may result. Site-specific variations of the fixed and design parameter will influence this ratio, but for the most part, case study documentation validates this trend, particularly for innerburden less than 110 ft. Under these conditions, pillars designed with lower limit safety factors (<1.5) may experience instability because of stresses produced after development of the second seam. Although the analysis in table 6 is derived from a rather limited data set and the results are not conclusive owing particularly to a lack of information on stability at greater and thicker innerburdens, this analysis does demonstrate the effects of increasing overburden-innerburden ratios on the stability of multiple room-and-pillar developments. When fixed parameters exceed the above criteria, pillar safety factors should be kept towards the upper limit of 2.2.

ALTERNATIVE DESIGN CONSIDERATIONS

Determining the proper size of pillars to withstand additional loads resulting from multiple-seam mining is a trial and error procedure, based mainly on experience. Overdesign or increasing pillar size is the most common solution to the problem, but for workings at depths greater than 1,000 ft and with high overburden-innerburden ratios, this approach may not be practical. For example, redesign pillars in case 3 using an upper limit of pillar stress (σ_p) of four times the overburden load (7). Selecting a conservative pillar formula, such as the Bieniawski-Pennsylvania State University formula and back calculating, a 150-ft-square pillar is required. Maintaining the same entry width of 18 ft, the pillar safety factor is increased to 3.2, but percent extraction is reduced to 0.20. This is unacceptable for maintaining a profitable mining operation.

Unique solutions for maintaining profitable yet stable multiple room-and-pillar operations at depth may be sought in the application of yield pillars or stiff-yield pillar systems. Yield pillars have been successfully demonstrated for improving gate entry stability in longwall mining, but are relatively unproven in room-and-pillar panel developments. Yield pillars have been proposed by various researchers (12-13) and involve the application of pressure arch theory and techniques.

Arching theory assumes that the mine opening is the major structural element in the transfer of load. Load transfer is the result of the pressure arch that forms around a mine opening upon excavation. The arch is elliptical and exists both above and below the mine opening. As shown in figure 13 (14), it consists of an intradosal ground (tension zone) enveloped by an extradosal ground (compressive zone). The pillars support the extradosal ground, which is known as the abutment pressure. The magnitude of the abutment pressure and the shape and height of the arch are dependent upon the depth, the opening width, and the physical nature of the strata. In conventional room-and-pillar panels, independent arches can form from pillar to pillar (fig. 14). In a yield pillar panel, the pillars are designed to yield their load in a controlled manner and transfer it to larger barrier or abutment pillars forming a secondary arch (fig. 15). Applying this concept to multiple-seam operations, and practicing pillar superpositioning, in theory, a large arch would form and a destressed zone would be created between the two panel developments. Load transfer would then take place between the barrier pillars designed with large safety factors, rather than the individual panel pillars. Figure 16 illustrates the theoretical distribution of stress in a multiple-seam

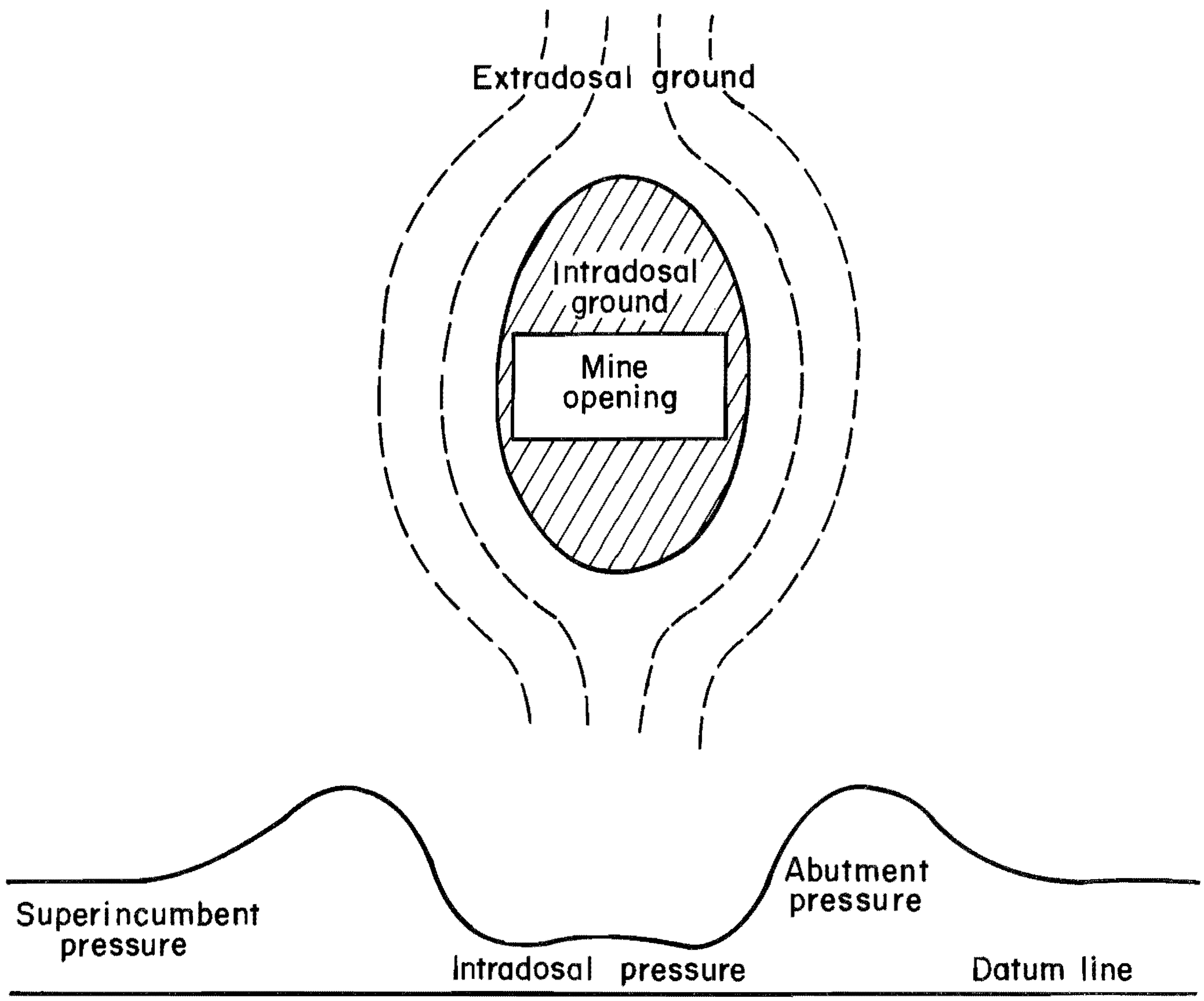

FIGURE 13.--Pressure arch around mine opening.

yield pillar system for workings in close proximity (<110 ft).

Hypothetical panel layouts using yield pillar in single-seam mining have been proposed by Holland (12) and Britton (13). Although these designs have been applied underground with limited extent, the results are encouraging for maintaining ground stability as well as a profitable extraction ratio. Before multiple-seam yield pillar systems can be successfully implemented underground, extensive and careful investigations must be conducted in both the laboratory and field. This research is necessary to improve the understanding of yield pillar behavior and related load transfer mechanisms.

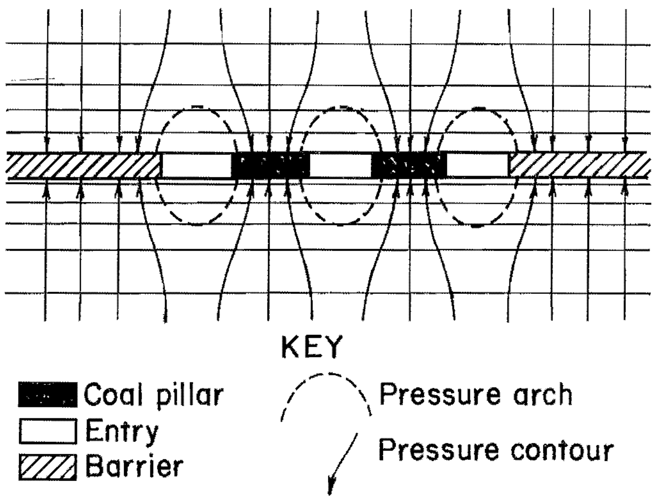

FIGURE 14.--Independent arches forming from pillar to pillar.

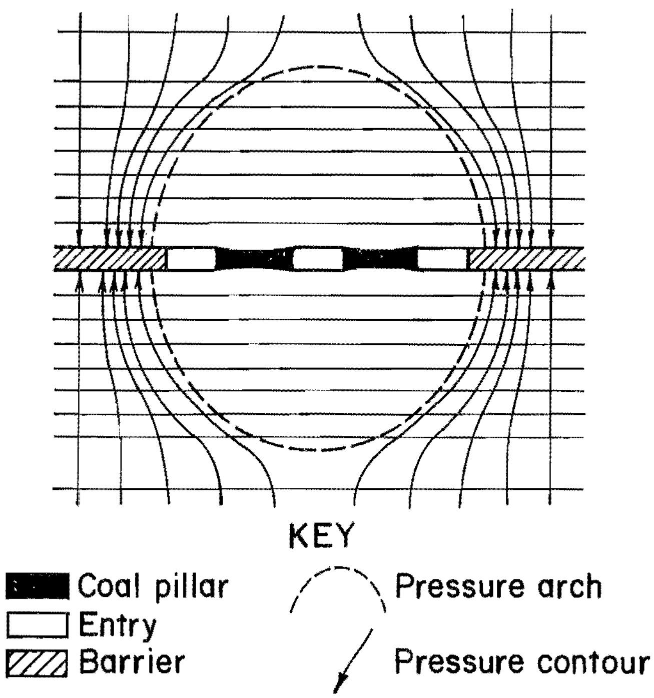

FIGURE 15.--Pillars yielding to form secondary arch.

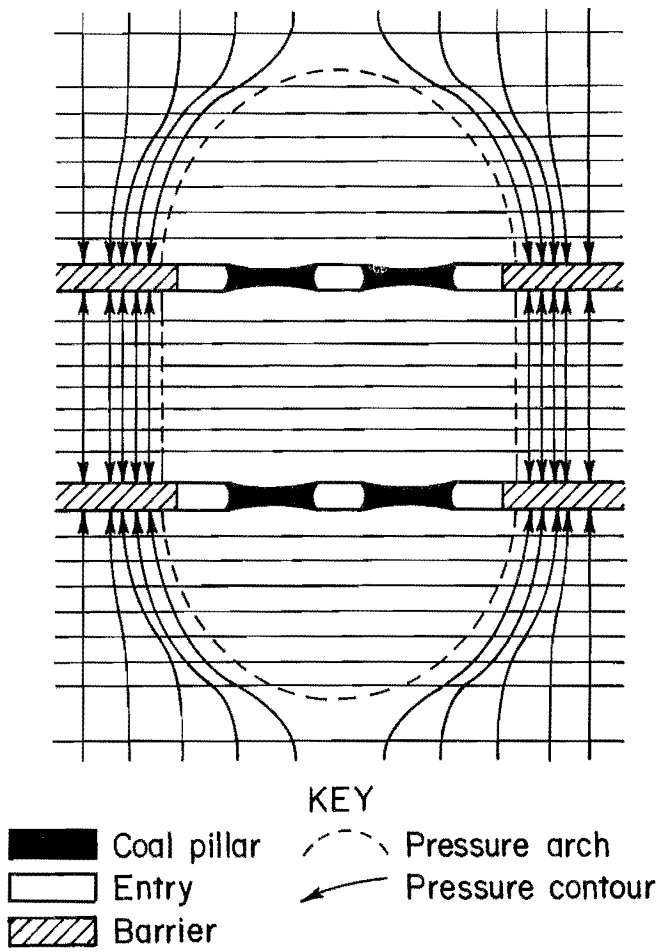

FIGURE 16.--Conceptualized behavior of yielding pillars for multiple-seam developments.

CONCLUSIONS

Controlling interactions between room-and-pillar developments in close proximity (<110 ft) to one another is essential for maintaining a profitable and safe multiple-seam operation. Workings at depth (>1,000 ft) with high overburden-innerburden ratios are particularly susceptible to load transfer. Theoretical designs have been proposed to control stresses at depth, but it can be concluded that no specific guidelines or design criteria have been widely accepted. Carefully planned research and engineering judgment, both theoretical and empirical, is necessary before successful yield pillar systems can be implemented. Geotechnical instrumentation for monitoring workings suspected of interaction, when combined with visual observation, is a feasible method for evaluating site-specific stability problems. Information such as rock strengths, entry convergence rates, and characteristic loadings of pillars can be correlated with the geologic environment and determinations made concerning the extent and magnitude of load transfer. Proper safety factors can then be established, within reason, for maintaining pillar stability.

From the research conducted at these three sites the following conclusions can be made:

1. Pillars that display a peak-trough loading, where the highest pressure occurs towards the pillar core, are most likely to transfer load. Pillars in case 3 displayed this characteristic loading, and both the upper and lower workings were very unstable as the ratio of average core pressure to average yield zone pressure was approximately 10:1. Pillars in cases 1 and 2 displayed loadings characteristic of more stable designs and there was little interaction between workings.

2. Research indicates that when overburden-innerburden ratio reaches or exceeds 8:1, a potentially unstable condition may result, especially for pillars with bearing capacities between 2,700 and 3,025 ft^2 and innerburdens less than 110 ft. Under these conditions, additional loads produced by second-seam development can cause stability problems for pillars with lower limit safety factors (<1.5). Using the ultimate-strength design approach, pillar safety factors should be kept near the upper limit of 2.2.

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APPENDIX.--DETERMINATION OF IN SITU COAL STRENGTH (8)[1]

CASE 1

Cubical specimens from the Lower Freeport Coalbed were prepared with side dimensions of 2 in. The average uniaxial compressive strength, σ_c, of the test cubes was determined to be 2,360 psi.

Research has shown (8) that the scaling of coal properties from cubical specimens to the in situ coal strength value can be obtained through the following equation:

$$\sigma_1 = \sigma_c \left(\frac{D}{36} \right)^{1/2}, \qquad \text{(A-1)}$$

where σ_1 = in situ coal strength, psi,

σ_c = uniaxial compressive strength of a 2-in cube specimen, psi,

and D = cube size dimension.

Therefore

$$\sigma_1 = 2{,}360 \left(\frac{2}{36} \right)^{1/2}$$

$$= 556 \text{ psi.}$$

CASE 2

Test specimens were prepared from 2-in-diam coal cores with a length-to-width ratio of 2. The core specimens had an average uniaxial compressive strength, σ_{spec}, of 2,200 psi.

Research has shown (8) the correction factor from the core strength, σ_{spec}, to the strength of 2-in cubical specimen, σ_c, can be obtained through the following equation:

$$\sigma_c = \sigma_{spec} \, [0.778 + 0.222 \, (1/D)] \qquad \text{(A-2)}$$

where σ_c = uniaxial compressive strength of 2-in cube specimen, psi,

σ_{spec} = uniaxial compressive strength of core specimen, psi,

l = length of core specimen, in,

and D = diameter of core specimen, in.

Therefore

$$\sigma_c = 2{,}200 \, [0.778 + 0.222 \, (4/2)]$$

$$= 2{,}690 \text{ psi.}$$

Substituting into equation A-1 to determine σ_1, the in situ coal strength

$$\sigma_1 = 2{,}690 \left(\frac{2}{36} \right)^{1/2}$$

$$= 634 \text{ psi.}$$

CASE 3

Test specimens were prepared from 2.1-in-diam coal cores with a length-to-width ratio of 1.15. The core specimens had an average uniaxial compressive strength, σ_{spec}, of 1,810 psi. Using equation A-2 to determine σ_c:

$$\sigma_c = \sigma_{spec} \, [0.778 + 0.222 \, (1/D)]$$

$$= 1{,}810 \, [0.778 + 0.222 \, (2.4/2.1)]$$

$$= 1{,}870.$$

Using equation A-1 to determine σ_1:

$$\sigma_1 = \sigma_c \left(\frac{D}{36} \right)^{1/2}$$

$$= 1{,}870 \left(\frac{2}{36} \right)^{1/2}$$

$$= 440 \text{ psi.}$$

[1]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

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