DEEP COVER PILLAR EXTRACTION IN THE U.S. COALFIELDS

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ABSTRACT

Deep cover retreat mining (overburden in excess of 750 ft) is an important emerging issue which will intensify in the future as the more easily mined shallow seam reserves are depleted. Analysis of Mine Safety and Health Administration (MSHA) statistics indicates that deep cover pillar recovery accounts for a disproportionate share of the underground coal mine roof/rib fall fatalities and injuries. Past research has shown that previously recommended Analysis of Retreat Mining Pillar Stability (ARMPS) stability factors (SF's) may be excessive for deep cover pillar design. The objectives of this study were to evaluate the various methods and strategies by which panels, production pillars and barrier pillars are developed and extracted under deep cover, and to develop appropriate design guidelines. In the course of the research, 29 mines in 7 states were investigated to collect panel design case histories. At each mine site, underground geotechnical data were collected on the pillar line in order to document roof rock, coalbed and floor conditions. The analyses indicated that squeezes were the most likely failure mode where the depth was less than 1,250 ft, but bumps predominated in the deeper cover cases. Immediate roof rock quality, the ARMPS SF's, and barrier pillar stability factors were all found to be important parameters in determining the outcomes of the case histories. Design guidelines, including suggestions for barrier pillars to isolate active panels from nearby gobs in bump prone ground, are also proposed.

INTRODUCTION

Over the past 2 decades, retreat mining has gained a disparaging reputation in terms of safety. Since 1978, approximately 25% of the roof/rib fall fatalities have occurred during pillar recovery operations. However, retreat mining only accounts for about 10% of the total U.S. underground coal production (1). Since 1997, deep cover (overburden in excess of 750 ft) pillaring operations have accounted for 40% of the fatalities which have occurred during pillar recovery. To put this in perspective, Mine Safety and Health Administration (MSHA) Roof Control Specialists from across the country were surveyed and 48 deep cover pillaring operations were identified. In addition, comparative evaluations conducted by National Institute for Occupational Safety and Health (NIOSH) personnel of MSHA data (2) determined that ground fall incidence rates were 27% higher for deep cover retreat mining operations as compared to all other room-and-pillar mines.

Realizing that deep cover pillar recovery was an important emerging issue which will intensify in the future as mines are forced to go deeper, NIOSH investigators began examining the situation in 1997. Because there were relatively few prior research efforts in the area of ground control for deep cover pillar extraction, NIOSH personnel went to the coalfields to document the actual experiences of the operators. The underlying premise was that information gathered by documenting the trial-and-error/success panel design refinement processes of several mining operations should yield valuable design guidelines and strategies. This in the same research methodology that proved successful in generating and validating the Analysis of Retreat Mining Pillar Stability (ARMPS) computer program (3) which today is widely used to size pillars for retreat mining.

Analyses of approximately 150 case histories in the original ARMPS database found that where the depth of cover is less than 750 ft, a Stability Factor (SF) of about 1.5 is normally a reasonable starting point. However, for the deep cover cases two conclusions were drawn (3, 4):

- Many panels with a SF less than 1.5 were successful, but;
- No single SF seemed to be an appropriate design criterion.

The goal of this study was to develop appropriate criteria for applying ARMPS to size pillars for deep cover, and determine what other significant factors should be considered in design. In order to accomplish this objective, 97 panel design case histories were gathered at 29 mines located in the following states: CO, KY, PA, TN, UT, VA, and WV. Underground geotechnical data on the immediate roof rock, coalbed, and floor conditions were collected for each case history. Due to the fact that limited core hole data was available at several mines in the immediate vicinity of the case history, the main roof rock's composition, strength, and caving characteristics could not be considered. Obviously, this was unfortunate because the characteristics of the main roof can play an important role in determining the outcome of a particular design, for example, the likelihood of a bump occurring. Also, excluded from the data base were any panels which were over- or undermined. During this investigation, careful attention was also paid to documenting the various methods and strategies by which panels, production pillars and barrier pillars were developed and extracted to determine the current state-of-the-art. In order to select mine sites representative of the deep cover population, the opinions of several Roof Control Specialists from the Mine Safety and Health Administration (MSHA) and State Department of Mines personnel throughout the country were solicited.

GROUND CONTROL CONCERNS

Hazards associated with pillar extraction tend to intensify with depth. Pillar failures, including both bumps and squeezes, are generally more severe at depth and are evidence of a highly stressed environment. Bumps are sudden violent pillar failures where the coal is expelled into the workings. Documented bumps in the deep cover database have caused fatalities, serious injuries, personnel entrapments, and/or equipment damage. Many of these events shook the surface facilities and adjacent mine workings. As compared to shallow cover pillar extraction, there is an audible increase in coal pillar popping and roof thumping and bouncing at greater depths.

Squeezes (also called rides or pillar runs) are nonviolent gradual pillar failures that cause noticeable coal sloughage and roof-to-floor convergence. It may take hours, days, or even weeks for a section to squeeze. As the pillars steadily fail, the overlying strata settle and the roof may break. Some squeezes which have occurred during idle shifts have resulted in equipment entrapments. Also, extensive portions of panels and mains have been abandoned due to squeezes.

Other effects of a deep cover high stress regime can include excessive roof falls, pillar spalling, and floor heave. Failed panel design case histories attributed to roof falls were documented under both weak and competent immediate roof strata (Appendix 1). When mining under weak roof, the structural integrity of the rock may be sufficient enough to withstand development stresses; however, the strata may fail later when subjected to retreat mining induced abutment stresses, as was the case in a Colorado mine visited. Conversely, the beam building ability of a strong immediate and main roof rock units may inhibit caving. This can generate inordinate pillar line stresses, which, in turn, can produce severe pillar sloughage and floor heave. As the size of the worked-out area expands, the bridging capability of the roof may be exceeded and it caves. The result can be a powerful and potentially hazardous air blast. A sudden failure of a massive roof unit can also produce a hazardous "feather edge"which can override the breakers into the workings. The feather edge fracture has a conchoidal appearance, and is essentially a brittle failure phenomenon. Feather edge failures have been responsible for several fatalities in Australia (5), and at least one pillar line fatality in the U.S.

Horizontal stress magnitudes also tend to increase with depth. Roof potting on development, cutters, and long running roof falls are all problems associated with horizontal stress. Horizontal stress may also be concentrated around the gob areas created by retreat mining. Some mines have experimented with stress control techniques like "advance-and-relieve" mining to improve conditions in operations subjected to high horizontal stresses (6, 7).

In thicker coalbeds, overstressed pillars are prone to severe spalling and pose a serious threat to underground miners. Since 1995, rib roll fatalities have averaged more than one per year. In high coal, miners almost always indicate that one needs to pay more attention to the ribs than to the roof. Highly cleated coalbeds are particularly hazardous because these planes of weakness can define huge vertical slabs of coal which can roll over without warning (figure 1). Some mines experiencing cleat related rib rolls have been compelled to orient entries 45° to the face cleat to maintain safer travelways in both entries and crosscuts. However, this orientation can cause the cleat to segment the pillar corners into large triangular columns of coal which tend to fail into the intersections. After experiencing these various conditions, some operators have opted to drive entries at a low angle (25-30°) with respect to face cleat in an attempt to minimize rib sloughage problems.

Figure 1. Vertical coal pillar slabs associated with face cleat.

Floor failure can also be a deep cover operational issue. More typically, a competent roof tends to punch overstressed pillars into a weaker floor units causing heave in the roadways. Heave can be so extreme that equipment is not left in the working faces during idle shifts for fear of entrapment. Instances where it was necessary to use the continuous miners to regrade roadways for equipment clearance into the faces have also been documented. In one mine visited in southern West Virginia, approximately 4.5 ft of heave was observed just outby the pillar line in the 9 ft thick Beckley Coalbed (figure 2).

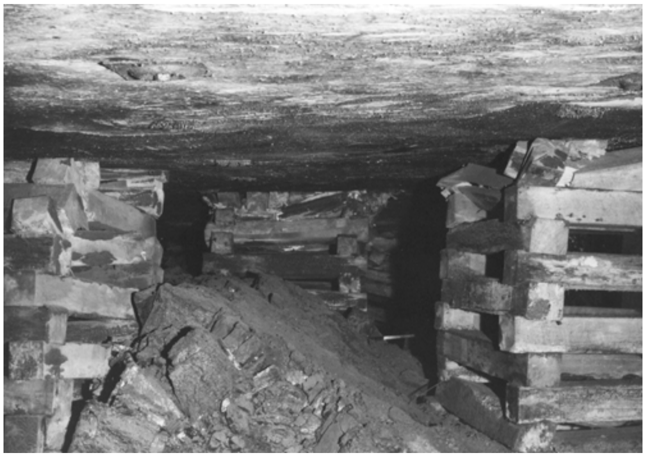

Figure 2. Excessive pillar line floor heave.

PANEL DESIGN

Coal mine operators have employed different production panel design philosophies under deep cover. One strategy employed is to develop a wide section (9 or more entries) the entire length of the panel on advance, and then recover the pillars on retreat. With this approach, large production pillars are developed with the intent that they, and the adjacent barrier pillar(s), should be able to withstand all anticipated loading conditions encountered during panel advance and retreat. One drawback to this full panel advance and retreat method is that at greater depths, the production pillars can become too wide to be fully extracted with single pass pillaring techniques. Most operators indicate that once the entry centers exceed 80 ft and leaving significant stumps is undesirable, pillar splitting before extraction becomes the only alternative if the pillars are to be fully extracted. Pillar splitting is generally not desired because it requires numerous place changes and roof bolting. In a thick coal high stress regime, rib rolls pose a serious threat to bolter operators and splitting is generally avoided. When conducting full panel advance and retreat, some operators slab cut the barrier pillar(s) as they pull the section back.

An alternative approach is the panel advance and rooming out on retreat method (figure 3). With this method, a narrow panel (4 or 5 entries) is advanced, leaving a large barrier between the section and the previous panel gob. On retreat, rooms are driven into the barrier, and then these and the panel production pillars are recovered all the way across the section. This technique is a modified version of the Old Ben method (8) which was used in Illinois in the 1960's and 1970's. One advantage of the panel advance and rooming method is that if problems are encountered on retreat, development into the barrier can be halted and a few rows of production pillars can be left intact so as to contain or isolate the problems inby.

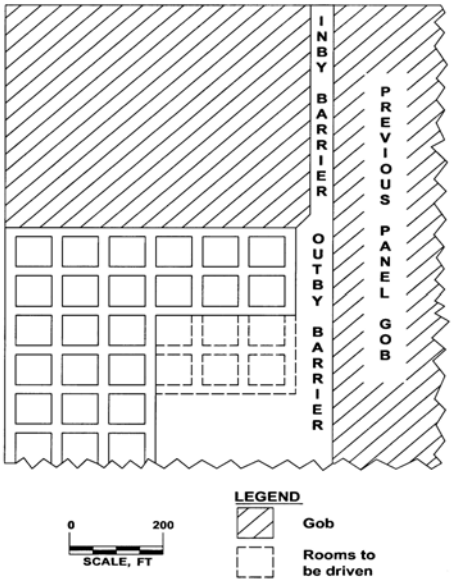

Figure 3. Panel advance and rooming out on retreat mining method.

The "thin-pillar" technique is a variant of the panel advance and rooming method which has been used for bump control (9). With this approach, both development entries and rooms are driven on narrow centers to create pillars that are designed to yield as they are developed. The goal is to have the minimum amount of ground opened up at any time. However, extremely serious problems can arise if the pillar sizes, extraction sequence, timing, etc., are not designed and executed properly. If pillars are too large to yield yet too small to withstand the applied loadings, they can be prone to squeezes or bumps.

Barrier pillars are an essential element in deep cover retreat mine design. Traditionally, barrier pillars have been employed to isolate active panels from adjacent gobs as a stress control technique. As the cover deepens, it becomes more important to isolate the active panel from side abutment loads transferred from the adjacent mined out workings by employing barriers pillars. An important design issue is just how wide the final remnant or inby barrier pillar (after rooming and/or slabbing) should be (figure 3). This topic is a critical and life threatening design concern in highly stressed environments because of the historically high occurrence of bump incidences during partial and full barrier pillar extraction (10). Campoli et al. (11) proposed just such a design method for sizing barrier pillars under deep cover. In the example he provided, no barrier was needed when the cover was less than 1,000 ft, but then the suggested barrier pillar width ranged from 150 to 240 ft as the cover increased from 1,200 to 2,200 ft. It should be noted that leaving large remnant barrier pillars can cause loads to transfer to seams above and below. Therefore, when mines are in multiple seam configurations, pillar load transfer should be anticipated. Pillar load transfer can cause various ground control problems (12), including bumps (10).

PILLAR EXTRACTION METHODS

Deep cover operators practice both full and partial production and barrier pillar recovery during panel retreat. An operator's rationale for electing one extraction method over another is usually based on factors including: equipment and timber availability and cost, pillar size, coalbed thickness, roof competency, and local custom. Approximately two thirds of the panels in the data base were extracted using either the Christmas tree or split and fender extraction methods (13). Of the two techniques, Christmas treeing is usually the one most favored by operators because it does not require place changes and bolting. Another extraction method practiced to fully recover large pillars is the pocket and wing procedure (13) which also requires place changes and bolting. Some operators indicated that if large pillars require splitting, that the split and fender method is preferred because if minimizes gob exposure as compared to the pocket and wing technique. In five panel designs studied, the outside lift method was used. In order to fully extract a pillar using this process with 40 ft extended cut lengths, the section needs to be driven up on narrow centers (60 ft or less).

The most commonly cited reasons for opting for partial pillar recovery were safety and/or productivity. Some operators indicated that the roof rock in their mines was weak and sometimes fell prematurely on the pillar line. They also felt that the remnant stumps which remained after pillar recovery acted like coal cribs and provided just enough load bearing capacity to support the roof during the extraction process. Partial pillar recovery also reduces the number of turn posts required to extract a pillar. The sacrificed coal is justified based on safety and/or economics. In high coal, setting posts weighing 175 pounds or more requires three miners. One miner has to climb a step ladder which in itself can be hazardous. In addition, because far fewer posts are set during partial pillar recovery, miners minimize their exposure to rib rolls in high coal. Economically, setting posts is expensive and reduces production time. This is especially true in western mines where there is a scarcity of inexpensive hardwoods. In some of the 12 ft plus thick western reserves, some operators notion of retreat mining is only to mine the floor coal. To combat the posting issues, several operators have turned to mobile roof support usage (figure 4).

Figure 4. Full pillar extraction using mobile roof supports.

One of the more favored partial pillar recovery techniques is pillar splitting. Most typically the pillars are designed on narrow entry centers (60 ft or less) and crosscut centers are usually 100 ft or less. On retreat, from one to three extended cut lifts (splits) are taken from the entry or crosscut. Another popular partial pillar recovery method is slabbing, where successive adjacent lifts are removed from a pillar leaving a significant saw toothed remnant stump. These lifts are usually taken from the entry. If lifts are also taken from the crosscut, this technique is referred to as “L” slabbing (figure 5). When practicing partial pillar recovery under competent roof rock which does not cave, the possibility of a massive remnant pillar collapse occurring in the mined out workings is a distinct possibility. These events should be considered and preventive measurements taken because both the roof fall and the resultant air blasts can be life threatening and devastating (14).

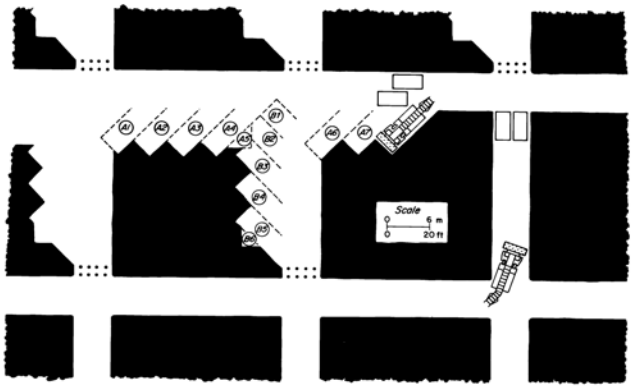

Figure 5. “L” slabbing on a super section using mobile roof supports.

Most typically, pillars developed by mining into the barrier are extracted in the same manner as are the production pillars in the panel. One noticeable exception is a variation of the wongawilli technique (15) employed by a few southern WV mines. With this method, four rooms, up to 200 ft long, are driven on 50 ft centers into the barrier. The 30 ft pillars are then extracted by taking consecutive lifts as shown in figure 6.

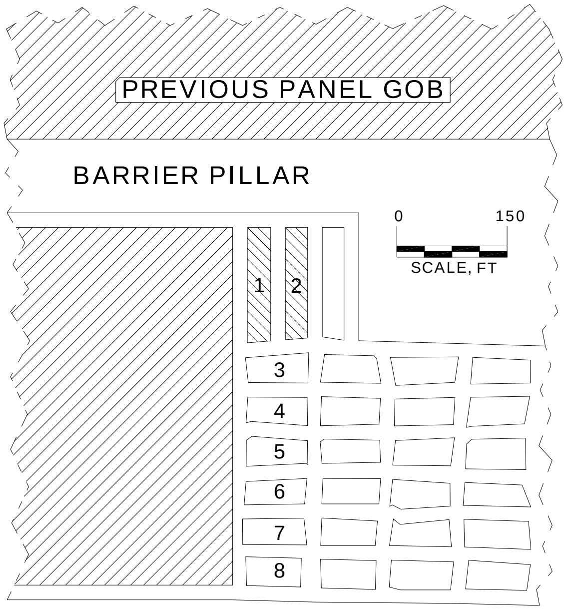

Figure 6. Barrier pillar development and extraction using a modified wongawilli technique.

DESCRIPTION OF THE DATA BASE

During this investigation, 97 panel design case histories were gathered at 29 mines located in 7 states. At each mine, underground geotechnical data on the immediate roof rock quality, coalbed, and floor conditions were collected. Careful attention was also paid to documenting the various methods and strategies by which panels, production pillars and barrier pillars were developed and extracted. The following parameters were determined for each case history:

- Roof Quality was evaluated using the Coal Mine Roof Rating (CMRR) system (16). The case histories were categorized as having weak (CMRR <45), intermediate (45<CMRR<65), and strong (CMRR>65) immediate roof rock conditions;
- Panel Advance Width;
- Panel Retreat Width (the panel advance width, plus rooms driven into and/or slab cuts taken from the barrier pillar(s) on retreat);
- ARMPS SF using the normal default valves for in situ coal strength and the active mining zone;
- Barrier Pillar SF determined using the ARMPS computer program, and;
- Outcome, either success, squeeze, bump, or panel abandonment due to excessive roof falls.

When examining the data base (figures 7-9), it was readily apparent that there were only a handful of weak immediate roof rock cases. A total of 8 weak immediate roof rock cases were collected, and half of those were failures. In addition, the deepest successful weak roof rock case history occurred at approximately 850 ft. Given the fact that 60% of the deep cover mines were investigated during this study, the authors contend that the scarcity of weak roof rock case histories is indicative of the deep cover mine population, and does not signify a data base quirk. Quite simply, based on past experiences, operators have determined that it is not feasible to mine under weak roof conditions in a deep cover, high stress regime. As for the remaining case histories in the data base, they were fairly evenly divided between “intermediate” and “strong” roof rock categories.

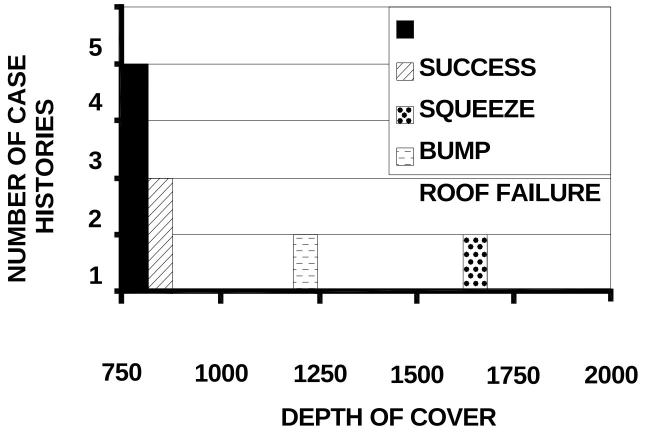

Figure 7. Deep cover weak roof rock data base.

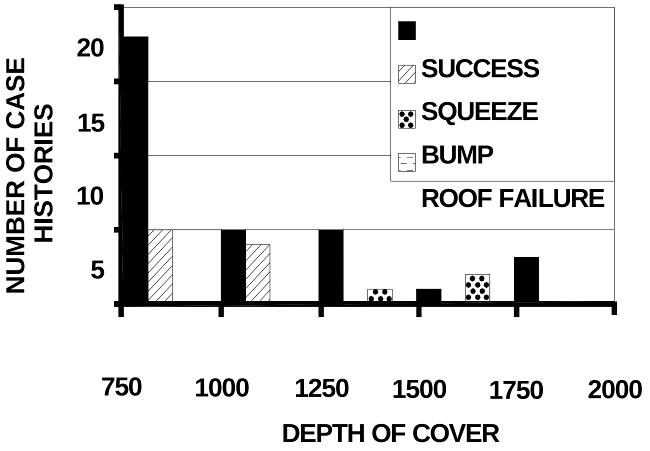

Figure 8. Deep cover intermediate strength roof rock data base.

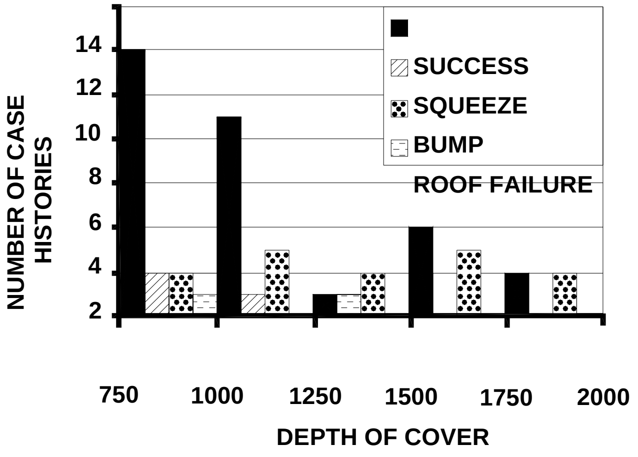

Figure 9. Deep cover strong roof rock data base.

The data base includes 16 bump and 14 squeeze failures. It should be noted that a majority of the squeezes (70%) occurred in the intermediate roof strength category, while 76% of the bumps happened under strong immediate roof rock conditions. Figures 7-9 also show that when the depth of cover was less than 1,250 ft, most of the failed cases were squeezes. As for the immediate floor quality in the squeeze data base, 6 cases occurred where the floor was weak and 3 cases had an intermediate floor strength. Surprisingly, five squeezes happened in panels which had a strong immediate floor. In general, the bumps occurred under deeper cover and in wider panels as shown in Appendix 1. In the bump data base, it is important to note that in 64% of the cases barrier pillars were not employed to isolate active panels from adjacent side gobs.

The use of barrier pillars also varied with depth. In the cases that were shallower than 1,300 ft, only 40% of the active panels were separated from adjacent gobs by barrier pillars. Deeper than 1,300 ft, 68% of the panels used barrier pillars. Only 27% of the strong roof cases used barrier pillars, compared with 62% for the weak and intermediate cases. When the mines which were operating under strong roof did use barriers, the SF’s were often lower.

Another interesting observation was that all 21 ARMPS Loading Condition 2 case histories (3) were successful. In Loading Condition 2, side abutment load transfer does not occur because the adjacent panels (if any have been driven) have not been retreat mined. Therefore, the program considers these areas as being unmined coal or, infinitely large barrier pillars.

DATA ANALYSES

Figure 10 compares the ARMPS SF’s, depth of cover and outcomes for approximately 250 shallow, moderate and deep cover panel design case histories. Analyses indicate that an ARMPS SF of 1.5 or greater is appropriate where the depth of cover is less than 650 ft. As the cover increases from 650 to1,250 ft, there seems to be a decreasing trend in SF’s for both the successful and the unsuccessful cases. However, deeper than 1,250 ft, there does not seem to be any clear trend. These observations, combined with the fact that the most common failure mechanism shifts from a squeeze to a bump at approximately 1,250 ft of cover, seems to justify separating the data into two groups by depth. Logistic regression was used to analyze the two groups. The failures were weighted as two in order to balance the data. Because of the small number of weak immediate roof rock cases, they were added to the intermediate strength roof rock category.

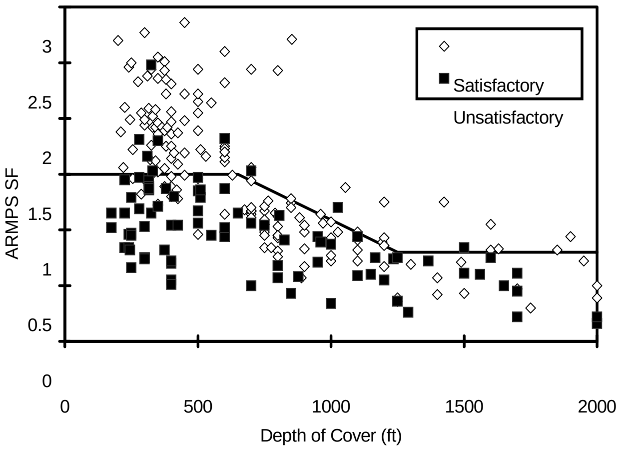

Figure 10. ARMPS case history data base.

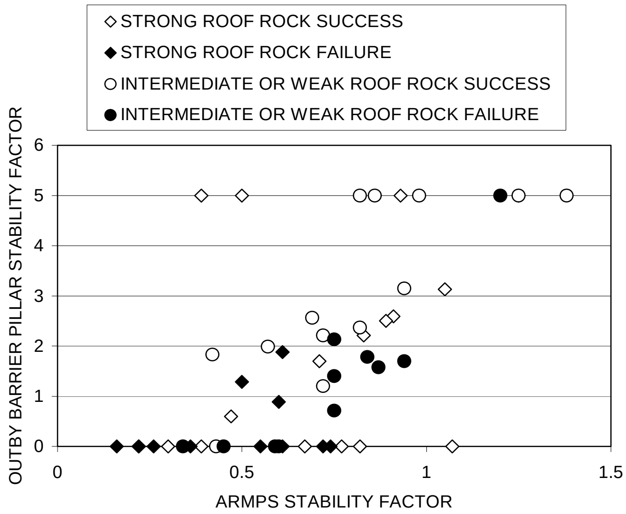

Figure 11. ARMPS and barrier pillar stability factors for the overburden exceeding 1,000 ft. data base.

Table 1. Pillar design considerations

Immediate roof rock quality	Weak and intermediate roof strength	Strong roof
ARMPS SF		
650 ft < H ≤ 1,250 ft	$1.5-\left(\frac{H-650}{1000}\right)$	$1.4-\left(\frac{H-650}{1000}\right)$
1,250 < H ≤ 2,000 ft	0.9	0.8
Barrier pillar SF		
H > 1,000 ft	≥2.0	≥1.5[1] ≥2.0[2]

[1] Nonbump prone ground
[2] Bump prone ground

When considering the cover (H) group ranging from 650 to 1,250 ft, the only two variables which were significant at the 0.15 level were the immediate roof rock quality and the ARMPS SF. The analyses also confirmed that the necessary ARMPS SF could be reduced if the immediate roof is strong. For the deepest cover (H >1,250 ft) grouping, the only two significant variables at the 0.15 level were the immediate roof rock quality and the barrier pillar stability factor. Again, strong immediate roof permitted a reduction in the suggested SF. Figure 11 compares the ARMPS SF, barrier pillar SF and the outcomes for the 57 case histories where the depth of cover was 1,000 ft or greater. As shown in figure 11, out of 12 cases, only one failure occurred when the ARMPS SF was greater than 0.8 and the barrier pillar SF was greater than 2.0. Conversely, 30 case histories had an ARMPS SF less than 0.8 and a barrier pillar SF less than 2.0, and 60% of these cases were failed designs. Of these 18 failed designs, 13 were bump events. In addition, every bump case history collected had a barrier pillar SF of less than 1.9. Based on these analyses, conservative design guidelines are proposed in Table 1. It should be noted that when examining figures 10 and 11, there are numerous successful case histories with stability factors less than those suggested in Table 1. Therefore, the recommendations proposed in Table 1 should be considered as first approximation design guidelines which should be tempered with other cite specific variables deemed relevant based on past experiences and sound engineering judgement. Finally, regression analyses also indicated that narrower panels reduced the required SF, but only at the 0.25 significance level.

DISCUSSION

One of the rationales for this research endeavor was the observation that lower ARMPS stability factors may be successfully employed when mining at deeper cover. There are two plausible explanations for this:

- The actual pillar strengths of the larger pillars used at depth are greater than that predicted by Mark-Bieniawski formula used in ARMPS, or;
- The actual pillar loadings are less than ARMPS predicts.

Recent research indicates that the immediate roof strength may be related to pillar strength for squat pillars (large w/h ratios). For example, data collected by Gale (17) indicates a wide range in measured strengths for pillars having the same width-to-height ratio. He attributed these strength differences to pillar confinement or, lack thereof. Gale concluded that strong immediate roof rock units with high shear strength can generate greater pillar confinement which increases the pillars strength.

Pillar loading may be affected by both the geology and the depth of cover. Where dealing with strong roof members at depth, the beam forming ability of stiffer immediate and main roof rock units may more readily transfer and equally distribute the mining induced loads to nearby abutments and barrier pillars. Conversely, where mining under weaker roof, one would expect the load transfer to be more problematic. Using field stress measurements collected in some of the deeper Australian coal mines, Colwell et al. (18) back-calculated lower abutment angles than the 21° default angle which ARMPS uses. In fact, it was noted that: “the abutment angles calculated for the two deepest mines, are the smallest of any in the database, 5.9 and 8.5°.” An examination of the Australian database also indicates that for the most part, an abutment angle of 21° is reasonable for the generally shallow supercritical panels (panel depth to panel width ratio less than approximately 1.3). For the normally deeper, subcritical panels which have higher depth-to-width ratios (H/P), lower abutment angles are warranted.

In another relevant article, Heasley (19) using LAMODEL suggests that the constant abutment angle concept employed by ARMPS probably over predicts the amount of abutment load as the depth of cover increases. Heasley thought it unreasonable that the gob loading remain constant after H/P exceeds 1.3. Heasley contends that “if the overburden displacement is considered to be linearly proportional to the depth, and the gob material is strain-hardening, then the gob should support an increasing percentage of load as the panel gets deeper.” He also suggested that some type of systematic abutment angle reduction with increased depth might be more realistic.

In order to examine Heasley’s suppositions, the SF’s for the database were recalculated using adjusted abutment angles back-calculated from the laminated overburden model with a constant lamination thickness. As was expected, there was marked increase in calculated SF's for subcritical panels as the depth of cover increased. However, no apparent correlations between the adjusted SF's and panel performance could be established. A more concentrated effort in this endeavor is warranted if the pillar mechanics of deep cover recovery is to be fully understood.

CONCLUSIONS

1. Ground control problems associated with pillar extraction generally intensify with increased depth. Conditions responsible for failed panel design case histories documented during this investigation include: bumps, squeezes, or excessive roof falls which caused large portions of, or entire panels to be abandoned.

2. Past research suggests that under shallow to moderate cover, an ARMPS SF of 1.5 seems to be appropriate. The data collected during this investigation indicates that where the depth cover exceeds 650 ft, lower ARMPS SF's can be successfully employed. In the overburden range between 650 and 1,250 ft, immediate roof rock quality and ARMPS SF were determined to be the significant variables. Greater than 1,250 ft, roof rock quality and barrier pillar design were concluded to be the significant variables.

3. Currently, deep cover operators are more likely to employ barrier pillars where the depth of cover exceeds 1,300 ft; however, their usage is not as widespread as one would anticipate. The data collected during this investigation substantiates the utility of barrier pillars to isolate active panels from nearby gobs where the depth of cover exceeds 1,000 ft. This is especially true in highly stressed, bump prone ground conditions.

4. Analyses of the database indicates that roof rock quality is an integral component in the panel design process. ARMPS SF's for production and barrier pillars can be lower when the immediate roof is strong (CMRR>65). Conversely, under weaker roof conditions, operators should consider advancing narrower panels and deploying larger barrier pillars to isolate the active working from adjacent gob areas.

5. The data suggests that squeezes are the predominate failure mode in mines operating at moderate depths with intermediate strength immediate roof rock conditions. However, bumps typically occur at greater depth and under stronger roof rock units.

6. A conservative approach to panel design for deep cover pillar recovery is to advance a narrow panel which is separated from the adjacent gob with a large barrier pillar. On retreat, rooms can be driven into the barrier pillar to extract a portion of it. In bump prone ground conditions, past experiences and sound engineering judgement should be employed when determining how wide the final or inby barrier pillar should be so as to isolate the workings from adjacent gobs. Information collected during this investigation indicates that when the barrier pillar SF was greater than 1.9, no bumps occurred.

7. This investigation confirmed that there is a decreasing trend in satisfactory ARMPS SF's as the depth of cover increases. It is possible, as other researchers have postulated, that ARMPS's constant abutment angle concept over predicts the abutment loads and underestimates the gob loading in subcritical panel designs. In this case, some type of systematic abutment angle reduction with increased depth might be warranted. However, a greater understanding of deep cover pillar mechanics is necessary to calibrate this reduction and this topic warrants future research efforts.

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Appendix 1.--Deep cover case history data base

Name	Case	H	h	Pillar Size	Ext pct	w/h	LC	ARMPS SF	Outby BP width	Outby BP SF	Inby BP width	Inby BP SF	Panel advance width	Panel retreat width	Roof	Floor	Ext. meth.	Comments
CO Mine A	1	1,560	9	50 x 110	40	5.5	3	0.6	0	0	0	0	230	230	W	I	L Slab	Miners entrapped by coal pillar bump.
CO Mine B	1	800	11.5	65 x 70	41	5.6	2	0.95	-	-	-	-	780	780	I	I	2-1/2 OL from entry & floor coal	Satisfactory design.
CO Mine C	1	850	9	60 x 100	38	6.7	2	1.28	-	-	-	-	320	630	W	I	OL	Satisfactory design.
CO Mine C	2	850	9	50 x 110	40	5.6	2	1.2	-	-	-	-	370	470	W	I	OL	Satisfactory design.
CO Mine D	1	750	7	42 x 100	41	6	4	0.95	0 0	0 0	0 0	0 0	260	730	I	I	Partial OL	Satisfactory design.
CO Mine D	2	750	7	42 x 100	41	6	3	1.21	0	0	0	0	340	500	I	I	Partial OL	Satisfactory design.
CO Mine D	3	800	7	32 x 82	48	4.6	3	0.76	0	0	0	0	220	495	I	I	Partial OL	Satisfactory design.
CO Mine D	4	950	7	42 x 100	41	6	3	0.94	50	1.1	50	0.56	335	500	I	I	Partial OL	Several rows of pillars lost due to excessive loading under deepest panel cover.
CO Mine D	5	1,100	7	42 x 100	41	6	4	0.59	0 0	0 0	0 0	0 0	260	730	I	I	Partial OL	Three rows of pillars lost due to heave and sloughage under deepest panel cover.
CO Mine E	1	1,250	8.5	30 x 80	52	3.5	4	0.36	135 0	2.37 0	135 0	1.61 0	170	270	S	S	Double split & floor coal removal	Excessive heave and floor bumps caused panel to be abandoned.
CO Mine E	2	1,250	8.5	30 x 80	52	3.5	3	0.39	0	0	0	0	170	270	S	S	Single & double split and floor coal removal	Satisfactory design.
CO Mine E	3	1,250	8.5	30 x 80	52	3.5	3	0.36	0	0	0	0	170	370	S	S	Double split & floor coal removal	Satisfactory design.
CO Mine E	4	1,250	8.5	30 x 80	52	3.5	3	0.36	0	0	0	0	170	370	S	S	Double split & floor coal removal	Satisfactory design.
CO Mine E	5	1,700	8.5	30 x 80	52	3.5	4	0.22	130 0	1.8 0	130 0	1.0 0	170	370	S	S	Single & double split & floor coal removal	Overstressed pillars next to the barrier were abandoned due to severe bumping.
CO Mine E	6	1,750	8.5	30 x 80	52	3.5	3	0.3	0	0	0	0	170	370	S	S	Double split & floor coal removal	Satisfactory design.
CO Mine E	6	2,000	8.5	30 x 80	52	3.5	2	0.39	-	-	-	-	170	170	S	S	Single split and floor coal removal	Satisfactory design.

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Name	Case	H	h	Pillar Size	Ext pct	w/h	LC	ARMPS SF	Outby BP width	Outby BP SF	Inby BP width	Inby BP SF	Panel advance width	Panel retreat width	Roof	Floor	Ext. meth.	Comments
CO Mine E	7	2,000	8.5	30 x 80	52	3.5	4	0.16	125 0	1.5 0	125 0	.71 0	170	270	S	S	Double split & floor coal removal	Down dip pillars by barrier pillar and side gob bumped.
CO Mine E	8	2,000	8.5	30 x 80	52	3.5	4	0.22	125 0	1.6 0	125 0	1.0 0	170	270	S	S	Single split & floor coal removal	Richter 3.7 bump event shook surface facilities
CO Mine F	1	882	6.3	60 x 60	44	9.5	3	1.11	0	0	0	0	400	400	I	I	S&F	Satisfactory design.
CO Mine F	2	889	11	50 x 60	46	4.5	4	0.57	60 238	0.99 4.57	60 238	.49 4.84	520	680	I	W	S&F	Satisfactory design.
CO Mine F	3	961	5	50 x 60	46	10	3	1.14	65	1.97	65	1	280	280	I	W	S&F	Satisfactory design.
CO Mine F	4	961	5	50 x 50	49	10	3	0.89	0	0	0	0	420	420	I	W	S&F	Lost 3 rows of pillars due to excessive pressures.
CO Mine F	5	1,250	5	40 x 80	47	8	3	0.75	95	2.13	65	0.71	240	270	W	W	Xmas	Roof falls over-rode the breakers and the section was abandoned.
KY Mine A	1	878	8	61 x 61	42	7.6	4	0.58	0 0	0 0	0 0	0 0	340	340	S	S	S&F	Excessive pressures in pillar point caused 3 rows of pillars to be lost.
KY Mine A	2	1,166	7	61 x 61	42	8.7	3	0.75	29	0.71	29	0.18	340	570	I	S	S&F	Lost 6 rows of pillars in squeeze.
KY Mine A	3	1,193	7.2	61 x 61	42	8.5	3	0.89	160	2.5	160	2.2	340	560	S	S	S&F	Satisfactory design.
KY Mine A	4	1,235	6.7	61 x 61	42	8.7	3	0.74	0	0	0	0	340	590	S	S	S&F	Severe bump fatally injured 2 miners in pillar point.
KY Mine A	5	1,290	7	41 x 51	50	5.9	4	0.26	0 0	0 0	0 0	0 0	260	260	S	S	S&F	Moderate coal pillar bump pushed the continuous miner out of the lift.
KY Mine A	6	1,366	5	61 x 61	42	12.2	3	0.72	0	0	0	0	340	980	S	S	S&F	Lost 4 rows of pillars due to excessive pressures.
KY Mine A	7	1,489	8	61 x 81	38	7.6	3	0.71	140	1.7	130	1.1	340	450	S	S	S&F	Satisfactory design.
KY Mine A	8	1,630	7	61 x 81	38	8.7	3	0.83	140	2.21	140	1.31	500	500	S	S	S&F	Satisfactory design.
KY Mine B	1	1,300	4.5	36 x 61	50	8	3	0.69	110	2.56	65	0.78	350	380	I	S	Xmas	Satisfactory design.
KY Mine B	2	1,600	5	61 x 74.8	40	12.2	3	1.05	175	3.13	140	1.8	340	370	S	S	Xmas	Satisfactory design.
KY Mine B	3	1,700	5	51 x 61	44	10.2	3	0.47	50	0.6	20	0.04	625	655	S	S	Xmas	Satisfactory design.
KY Mine B	4	1,850	5	66 x 74.8	39	13.2	3	0.82	150	2.37	120	1.08	360	390	I	S	Xmas	Satisfactory design.
KY Mine B	5	1,950	5	66 x 71	39	13.2	3	0.72	150	2.21	115	0.92	360	390	I	S	Xmas	Satisfactory design.
KY Mine C	1	800	4.2	23 x 50	64	5.5	3	0.57	35	1.32	10	0.07	335	365	W	W	OL	Lost 14 rows of pillars in squeeze.

Appendix 1.--Deep cover case history data base

Name	Case	H	h	Pillar Size	Ext pct	w/h	LC	ARMPS SF	Outby BP width	Outby BP SF	Inby BP width	Inby BP SF	Panel advance width	Panel retreat width	Roof	Floor	Ext. meth.	Comments
KY Mine D	1	1,000	10	50 x 50	49	5	4	0.34	0 0	0 0	0 0	0 0	370	370	I	S	S&F	While retreating bottle necked mains, numerous fenders were lost due to excessive loading.
KY Mine E	1	775	6	35x60	53	5.8	3	0.84	80	2.24	40	0.53	355	440	I	I	Xmas	Satisfactory design.
KY Mine E	2	800	5.6	35x60	52	6.3	2	1.12	0	0	0	0	345	410	S	I	Xmas	Satisfactory design.
KY Mine E	3	800	6	35x60	53	5.8	3	0.81	80	2.16	40	0.51	360	440	I	I	Xmas	Satisfactory design.
KY Mine E	4	800	4.3	70x70	41	16.3	3	2.43	150	5.9	120	4.6	380	440	I	I	Xmas	Satisfactory design.
KY Mine E	5	1400	5.5	35x50	56	6.4	3	0.42	100	1.83	70	0.61	350	410	I	I	Xmas	Satisfactory design.
KY Mine E	6	1400	4.3	35x65	52	8.1	3	0.57	90	1.99	60	0.56	355	420	I	I	Xmas	Satisfactory design.
KY Mine E	7	1425	4.3	70x60	43	14	3	1.25	220	5.25	190	4.16	380	410	I	I	Xmas	Satisfactory design.
KY Mine E	8	1500	4.3	35x60	44	8.1	3	0.84	90	1.78	50	0.36	355	440	I	I	Xmas	Moderate bump caused face equipment damage.
KY Mine E	9	1600	4.3	60x65	44	14	3	0.75	75	1.4	45	0.27	370	435	I	I	Xmas	Severe bump pushed continuous miner back 15 feet out of the lift and broke the frame.
KY Mine E	10	1700	7.4	70x50	44	6.8	3	0.45	0	0	0	0	375	395	I	I	Xmas	Moderate bump events caused several pillars to be abandoned.
KY Mine E	11	1900	4.3	60x70	43	14	3	0.94	170	3.15	140	1.6	320	380	I	I	Xmas	Satisfactory design.
KY Mine F	1	764	5.7	35 x 60	52	6.1	2	1.26	-	-	-	-	350	240	S	S	OL	Satisfactory design.
PA Mine A	1	806	7.2	60 x 60	39	8.3	4	1.13	0	0	0	0	710	710	W	W	P&W	Lost 115 pillars overnight squeeze,
PA Mine A	2	853	7.2	70 x 80	34	9.7	2	2.71	-	-	-	-	539	539	W	W	P&W	Satisfactory design
TN Mine A	1	1,000	2.5	40 x 35	61	14	3	0.87	35	1.58	0	0	260	290	I	W	OL	Majority of panel lost due to squeeze.
TN Mine A	2	1,026	2.5	35 x 30	66	12	2	0.98	-	-	-	-	240	270	I	W	OL	Satisfactory design.
TN Mine A	3	1,026	2.5	35 x 30	66	12	3	1.2	180	9.87	180	14.7	240	240	I	W	None	Squeezed caused 2,200 ft of mains to be abandoned.
UT Mine A	1	1,200	8.4	65 x 65	0.42	7.7	2	0.86	-	-	-	-	350	440	l	I	L Slab	Satisfactory design.
UT Mine B	1	1,000	7	60 x 60	0.44	8.6	3	0.72	0	0	0	0	180	340	S	W	Partial Xmas	Satisfactory design.
UT Mine B	2	1,100	9	70 x 80	0.38	7.8	3	0.91	215	2.59	115	1.17	380	410	S	I	S&F	Satisfactory design.
UT Mine B	3	1,100	7	60 x 60	0.44	8.6	3	0.82	0	0	0	0	590	590	S	W	Partial Xmas	Satisfactory design.
UT Mine B	4	1,200	7.5	60 x 60	0.44	8	3	0.55	0	0	0	0	420	420	S	W	Partial Xmas	Moderate squeeze occurred at pillar point.
UT Mine B	5	1,200	9	80 x 70	0.38	7.8	2	0.93	-	-	-	-	400	600	S	I	S&F	Satisfactory design.

Appendix 1.--Deep cover case history data base

Name	Case	H	h	Pillar Size	Ext pct	w/h	LC	ARMPS SF	Outby BP width	Outby BP SF	Inby BP width	Inby BP SF	Panel advance width	Panel retreat width	Roof	Floor	Ext. meth.	Comments
UT Mine B	6	1,200	5.5	60 x 60	0.44	10.9	2	1.25	-	-	-	-	340	340	S	W	S&F	Satisfactory design.
UT Mine B	7	1,500	9	60 x 80	0.4	6.7	4	0.43	60 350	0.61 4.34	60 300	0.28 4.36	350	380	I	I	L Slab	Satisfactory design.
UT Mine B	8	1,600	9	70 x 80	0.38	7.8	2	0.82	-	-	-	-	380	410	I	I	L Slab	Satisfactory design.
UT Mine C	1	800	7.5	63 x 63	0.42	8.4	3	1.03	0	0	0	0	415	415	S	S	S&F	Satisfactory design.
UT Mine C	2	800	7.5	63 x 63	0.42	8.4	3	0.93	0	0	0	0	350	350	S	S	S&F	Satisfactory design.
UT Mine C	3	800	8.2	63 x 63	0.42	7.7	4	0.68	0	0	0	0	350	350	S	S	S&F	Excessive bumping caused panel abandonment. Panel located in ridge nose.
UT Mine C	4	1,000	8	63 x 63	0.42	7.9	3	0.77	0	0	0	0	350	350	S	S	S&F	Satisfactory design.
UT Mine C	5	1,000	8	63 x 63	0.42	7.9	2	0.93	-	-	-	-	1,100	1,100	S	S	S&F	Satisfactory design.
UT Mine C	6	1,200	6.6	63 x 63	0.42	9.5	3	0.67	0	0	0	0	250	250	S	S	S&F	Satisfactory design.
UT Mine D	1	1,500	9	60 x 60	44	6.7	3	0.61	145	1.88	145	1.48	500	415	S	S	S&F	Three rows of pillars bumped.
UT Mine D	2	1,650	9	60 x 60	44	6.7	3	0.5	105	1.29	105	0.88	500	420	S	S	S&F	A Richter 3.6 bump event occurred when 7 rows of pillars failed violently.
UT Mine D	3	2,000	9	60 x 60	44	6.7	2	0.5	-	-	-	-	500	425	S	S	S&F	Satisfactory design.
VA Mine A	1	1,700	5.5	60 x 60	44	10.9	3	0.61	0	0	0	0	340	340	S	S	S&F	Moderate coal pillar bump.
VA Mine B	1	790	5.5	35 x 50	55	6.4	2	1.15	-	-	-	-	240	240	W	W	2 Cut	Satisfactory design.
WV Mine A	1	970	5.5	40 x 60	50	7.3	2	1.06	-	-	-	-	440	470	I	W	Xmas	Satisfactory design.
WV Mine A	2	1,054	5	60 x 60	44	12	2	1.38	-	-	-	-	500	530	I	W	Xmas	Satisfactory design.
WV Mine B	1	750	8	50 x 70	44	5	2	1.17	-	-	-	-	580	580	S	S	S&F	Satisfactory design.
WV Mine B	2	750	8	50 x 70	44	5	3	1.04	59	1.53	59	0.84	580	580	S	S	S&F	Stable LC2 development pillars protecting mains failed after adjacent panel was pillared.
WV Mine B	3	800	7	50 x 70	44	7.1	3	0.95	0	0	0	0	440	440	S	S	S&F	Satisfactory design.
WV Mine B	4	900	6	50 x 70	44	8.3	3	0.98	45	1.15	45	0.48	470	470	S	S	S&F	Satisfactory design.
WV Mine B	5	1,000	6	70 x 70	40	11.7	3	1.07	0	0	0	0	560	560	S	S	S&F	Satisfactory design.
WV Mine C	1	1100	6	55 x 77	44	9.2	3	0.94	80	1.7	45	0.38	300	360	I	S	Xmas	Lost 4 rows of pillars in squeeze.
WV Mine C	2	1100	6	50 x 69	46	8.3	3	0.72	70	1.2	35	0.21	310	370	I	S	Xmas	Satisfactory design.
WV Mine C	3	1100	6.5	50 x 79	43	7.7	2	0.98	-	-	-	-	650	650	I	S	Xmas	Satisfactory design.
WV Mine D	1	750	7.5	40 x 80	47	5.3	4	0.84	80 0	1.99 0	50 0	.71 0	315	505	I	I	Xmas	Satisfactory design.
WV Mine D	2	750	7.5	50 x 70	44	6.7	3	1.05	45	1.29	45	0.59	360	360	I	I	2 cut	Satisfactory design.

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Name	Case	H	h	Pillar Size	Ext pct	w/h	LC	ARMPS SF	Outby BP width	Outby BP SF	Inby BP width	Inby BP SF	Panel advance width	Panel retreat width	Roof	Floor	Ext. meth.	Comments
WV Mine D	3	750	4.7	35 x 80	49	7.4	4	0.98	600	2.150	300	.420	300	465	I	S	Xmas	Satisfactory design.
WV Mine D	4	750	7.5	40 x 60	50	5.3	2	1.09	-	-	-	-	320	350	I	I	Xmas	Satisfactory design.
WV Mine D	5	900	4.7	35 x 70	51	7.4	3	1.04	0	0	0	0	300	465	I	S	Xmas	Satisfactory design.
WV Mine D	6	900	7.5	40 x 80	47	5.3	3	0.83	0	0	0	0	500	675	I	I	Xmas	Satisfactory design.
WV Mine D	7	950	7.5	40 x 60	50	5.3	3	0.71	60	1.59	60	0.83	560	560	I	I	Xmas	Heavily loaded outby workings caused panel to be abandoned.
WV Mine E	1	850	9	50 x 50	49	7.1	4	0.43	00	00	00	00	370	370	S	W	Xmas	Pillar point roof fall had continuous miner buried for 2 weeks. Excessive heave.
WV Mine E	2	900	7	50 x 50	49	7.1	3	0.67	0	0	0	0	440	620	S	I	Xmas	Satisfactory design.
WV Mine E	3	1,150	6	55 x 70	43	9.2	4	0.6	430	0.890	430	0.320	330	490	S	S	Split & Xmas	Pillar point bump caused lost time injury.
WV Mine F	1	825	4.5	50 x 50	49	11.1	4	0.91	00	00	00	00	440	440	S	S	P&W	Moderate bump occurred in pillar point.
WV Mine G	1	850	4.5	60 x 40	50	8.9	2	1.24	-	-	-	-	660	660	S	I	Xmas	Satisfactory design.

Legend:
BP - barrier pillar
Ext pct - extraction percentage on advance
h - mining height
H - overburden
I - intermediate rock strength
LC - loading condition
OL - outside lift
P&W - pocket and wing
S - strong rock strength
S&F - split and fender
SF - stability factor
W - weak rock strength
w/h - width-to-height ratio
Xmas - Christmas tree