

PREVENTING MASSIVE PILLAR COLLAPSES IN COAL MINES

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ABSTRACT

A massive pillar collapse occurs when undersized pillars fail and rapidly shed their load to adjacent pillars, which in turn fail. The consequences of these chain-reaction failures can be catastrophic. One effect of a massive pillar collapse can be a powerful, destructive, and potentially hazardous airblast. Thirteen recent massive pillar collapses have been documented in West Virginia, Ohio, Utah, and Colorado. Data collected at the failure sites indicate that all of the massive collapses occurred where the pillar width-to-height (w/h) ratio was 3.0 or less and where the Analysis of Retreat Mining Pillar Stability Factor was less than 1.5. The unique structural characteristics of these pillar systems apparently result in sudden, massive pillar failures, rather than the more common slow "squeezes." The field data, combined with theoretical analysis, provide the basis for two partial-extraction design approaches to control massive pillar collapses. These are the *containment* approach and the *prevention* approach; practical examples are provided of each.

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INTRODUCTION

Massive pillar collapses in room-and-pillar mines have also been labeled "cascading pillar failures," "domino-type failures," or "pillar runs." In this type of failure, when one pillar collapses, the load that it carried transfers rapidly to its neighbors, causing them to fail, and so forth. This failure mechanism can lead to the rapid collapse of very large mine areas. In mild cases, only a few tens of pillars might fail; however, in extreme cases, hundreds, even thousands, of pillars can collapse.

Massive pillar collapses can have catastrophic effects on a mine. Sometimes these effects pose a greater safety risk than the underlying ground control problem. Usually, the collapse induces a devastating airblast due to the displacement of air from the collapsed area. An airblast can totally disrupt the ventilation system at a mine by destroying ventilation stoppings, seals, and fan housings. Flying debris can seriously

injure or kill mining personnel. The collapse might also fracture a large volume of rock in the pillars and immediate roof and floor. In coal and other gassy mines, this fragmentation can lead to the sudden release of large quantities of methane gas into the mine atmosphere, creating an explosion hazard. Finally, a massive pillar collapse can release significant seismic energy that may be experienced on the surface as a small earthquake.

Fortunately, not all pillar failures are sudden, massive collapses. Most are slow "squeezes" that develop over days to weeks, and because of their slow progress, do not pose as great a danger to mining personnel. A central goal of the research described in this paper was to identify the physical characteristics that distinguish sudden collapses from other pillar failures.

CASE HISTORIES

The most infamous massive pillar collapse in history occurred in 1960 at Coalbrook North Colliery in South Africa. Thousands of 12- by 12- by 4.2-m (40- by 40- by 14-ft) pillars collapsed over a 305-ha (750-acre) area in 5 min, killing 437 miners [Bryan et al. 1966]. Numerous other, smaller collapses have been reported in South Africa since then [Madden 1991]. In Australia, the New South Wales Joint Coal Board reported eight massive pillar collapses between 1990 and 1993 [University of New South Wales School of Mines 1994].

Massive collapses have also occurred in metal and nonmetal mines. Zipf and Mark [1996] documented six examples from lead-zinc, copper, silica, and salt mines. The largest occurred at a Wyoming trona mine in 1995, where 160 ha (400 acres) of 4- by 29- by 6-m (13- by 95- by 19-ft) fenders collapsed, resulting in a Richter magnitude 5.3 earthquake and one fatality underground [Ferriter et al. 1996]. The ventilation system at the mine was heavily damaged, and an estimated 1 million m³ (30 million ft³) of methane was liberated on the day of the collapse. Methane release levels did not return to normal until 3 months later [Ferriter et al. 1996].

In 1992, the former U.S. Bureau of Mines (USBM) was asked to investigate a massive pillar collapse and resultant destructive airblast that had occurred in a coal mine in Mingo County, WV. Subsequent investigations found 12 other examples, which were documented by field investigations [Chase et al. 1994]. Geotechnical evaluations examined the competency of the immediate roof, as well as that of the main roof and its susceptibility to caving. The Analysis of Retreat Mining Pillar Stability (ARMPS) program [Mark and Chase

1997] was used to determine the pillar stability factors (SF). Four examples that illustrate different mining methods and effects are described in detail below.

PILLAR SPLITTING (MINE A)

Mine A is located in Mingo County, WV, and is extracting the 2.9-m (9.5-ft) thick Coalburg Coalbed. A 28-m (90-ft) thick massive sandstone unit with a compressive strength of 83 MPa (12,000 psi) formed the roof above the collapsed area. The Coal Mine Roof Rating (CMRR) of the immediate roof was calculated to be 74. Below the noncleated coalbed is 10.5 m (34 ft) of competent sandy shale and sandstone units. All roadways were 6 m (20 ft) wide.

In 1991, the panel shown in figure 1 was developed. All roadways were driven on 18-m (60-ft) centers and were under 85 m (275 ft) of cover. After the panel was completed, partial pillar recovery was begun. A 6-m (20-ft) wide split was mined through the middle of each pillar, and two 3- by 12-m (10- by 40-ft) fenders with an ARMPS SF of 0.75 remained. Because of the competency of the roof and the support provided by the regularly spaced uniform fenders, no caving occurred while the panel was being retreat mined. Three weeks after the panel had been abandoned, an area measuring approximately 140 by 155 m (450 by 500 ft) containing 107 fenders collapsed. Miners on a nearby section were knocked to the floor by the resultant airblast. One miner was bounced off of a steel rail and required 26 stitches to his head. Fortunately, no miners were near the collapse. However, if the failure had occurred 15 min later, two miners would have

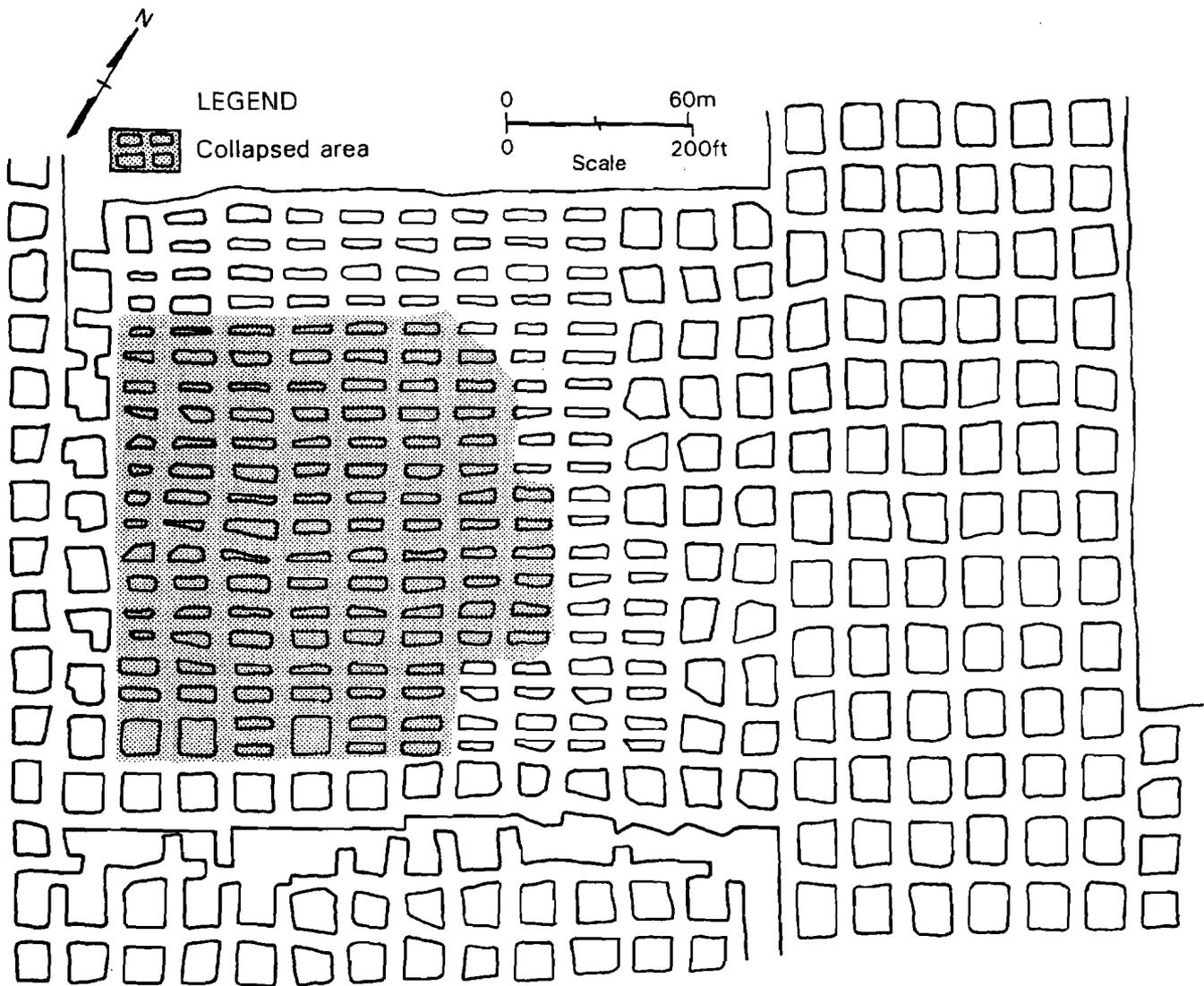


Figure 1.—Failed split-pillar workings in Mine A.

been rock dusting ribs immediately outby the area that collapsed. The airblast blew out 26 cinder block stoppings and the fan house weak wall, which closed the mine for days.

As was the case in many of the other collapses that were studied, a number of fenders near the edge of the collapse did not fail. There are two possible explanations for this: (1) The collapse might terminate as soon as the competent roof units were able to bridge the span, or (2) the collapse might terminate where the fenders were shielded from the full load by the adjacent abutment. In the second case, the 12- by 12-m (40- by 40-ft) pillars with an SF of 2.33 may have provided a hinge line, which allowed the roof to cantilever over the first several rows of fenders.

An earlier collapse had occurred at Mine A in partially pillared workings under very similar conditions. Damage was

limited to blown out stoppings, and no one was injured. Complete documentation of this case was unavailable.

After the second collapse, the practice of pillar splitting was reexamined at the mine. Several sets of mobile roof supports were purchased, and retreat mining continued with full pillar extraction. Most recently, some pillar splitting has been conducted, with rows of unsplit pillars left as barriers to isolate retreated areas.

PILLAR SPLITTING/ABUTMENT LOAD OVERRIDE (MINE C)

Mine C is located in Logan County, WV, and is extracting the 3-m (10-ft) thick Dorothy Coalbed. The immediate and main roof throughout the mine is composed of a fine-grained,

semilaminated sandstone with a CMRR of 64; the floor was composed of an extremely firm sandstone. Coalbed cleating was nonexistent. All roadways in the mine were 6 m (20 ft) wide and were driven on 18-m (60-ft) centers in the relevant area.

In 1992, the operator was splitting pillars in the panel shown in figure 2. After the 6-m (20-ft) wide split, two 3- by 12-m (10- by 40-ft) fenders with an SF of 0.94-1.15 remained. When the operator began to mine the pillar row outby the last row split (figure 2), a massive collapse of the fenders in the gobbed-out area initiated. The roof bolter operator on the section indicated that he and his coworkers were knocked to the floor by the resulting airblast, and 103 stoppings were destroyed. The pillars where the collapse terminated had an SF of 1.97. Overburden in the collapsed area ranged from 53 to 66 m (175 to 215 ft).

A subsequent pillar collapse occurred at Mine C, apparently triggered by time deterioration and front abutment pressures generated by full pillar extraction. Roadways in the collapsed area were driven on 15-m (50-ft) centers, and 91 pillars with an SF of 1.08 failed. Pillars with an SF of 1.69 halted the collapse. These roadways were driven on 18-m (60-ft) centers. No stoppings were damaged, and the overburden in the area was 99 m (325 ft).

Mine C was visited in February 1994 to observe diagonal pillar splitting, which is not a common practice. Roadways were driven on 15-m (50-ft) centers, and the pillar splits were 5 m (16 ft) wide. The extraction percentage was 86%. The triangular remnant stumps were observed to routinely crush out after finishing the pillar row, and the roof caved immediately in by the breakers. The breakers and wedges

showed no weight. Where the first pillar collapse occurred in Mine C using the traditional 6-m (20-ft) wide split through a 12- by 12-m (40- by 40-ft) pillar, 78% of the coal was extracted. This 8% increase in resource recovery, coupled with a less stable triangular stump with a smaller perimeter, probably explains why the roof caves more readily than in traditional pillar splitting.

SMALL-CENTER MINING (MINE D)

Mine D is located in Mingo County, WV, and is extracting the 3.4-m (11-ft) thick Dorothy Coalbed. The roof consisted of 76 cm (2.5 ft) of laminated fossiliferous shale and 7 cm (3 in) of rider coal, and 25 m (80 ft) of cross-bedded sandstone was observed in the highwall. The roof had a CMRR of 81. Below the noncleated coalbed was 1.5 m (5 ft) of sandy shale and 28 m (91 ft) of sandstone. All roadways in the mine were 6 m (20 ft) wide.

In 1992, ninety-four 6- by 6-m (20- by 20-ft) pillars with an SF of 1.15 and thirty-two 9- by 9-m (30- by 30-ft) pillars with an SF of 1.45 failed. As shown in figure 3, the pillar failures occurred in a panel driven off the mains. The resultant airblast blew out 37 stoppings. The only other stopping in the mine had a hole in it. Some of these stoppings were as far away as 244 m (800 ft) from the perimeter of the collapse. In one stopping, it was determined that some of its 14-kg (30-lb) cinder blocks had been hurled 152 m (500 ft). Fortunately, the occurrence was on an idle shift, and no one was in the mine. The collapse was halted by pillars in the main entries, which were 12- by 12-m (40- by 40-ft) and had an SF of 3.33. Cover over the collapsed area was 69 m (225 ft).

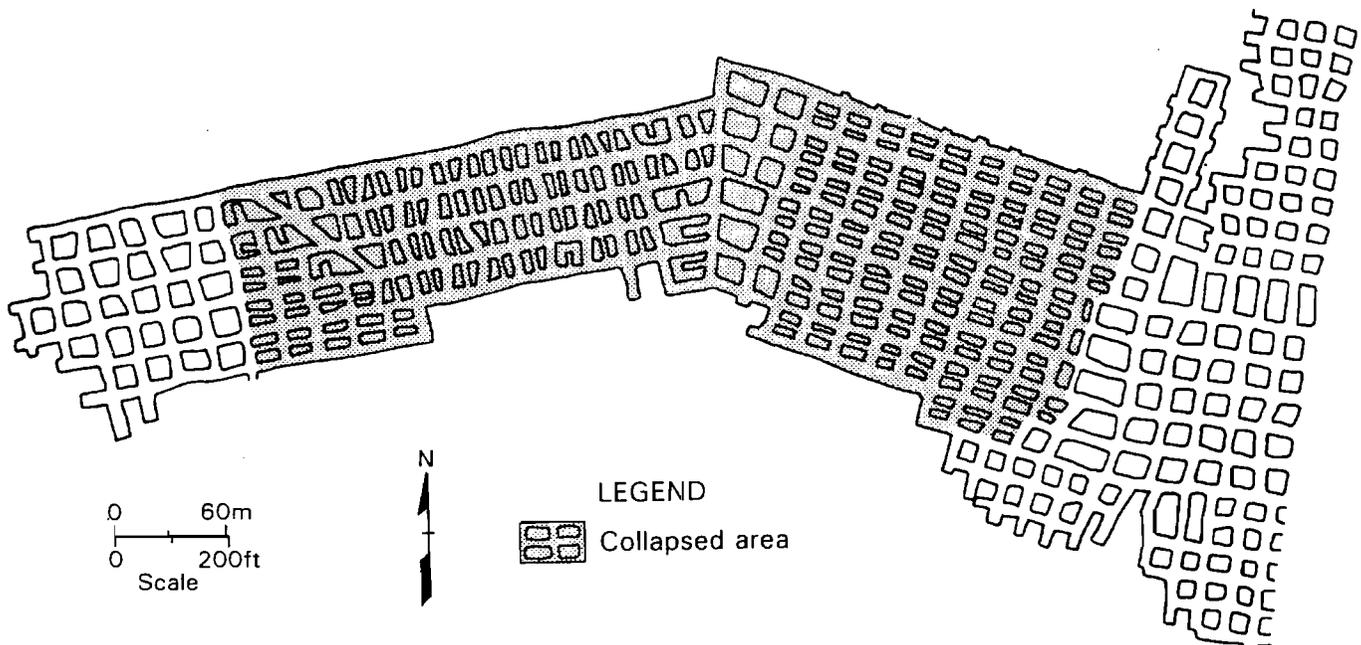


Figure 2.—Location of split-pillar collapse at Mine C.

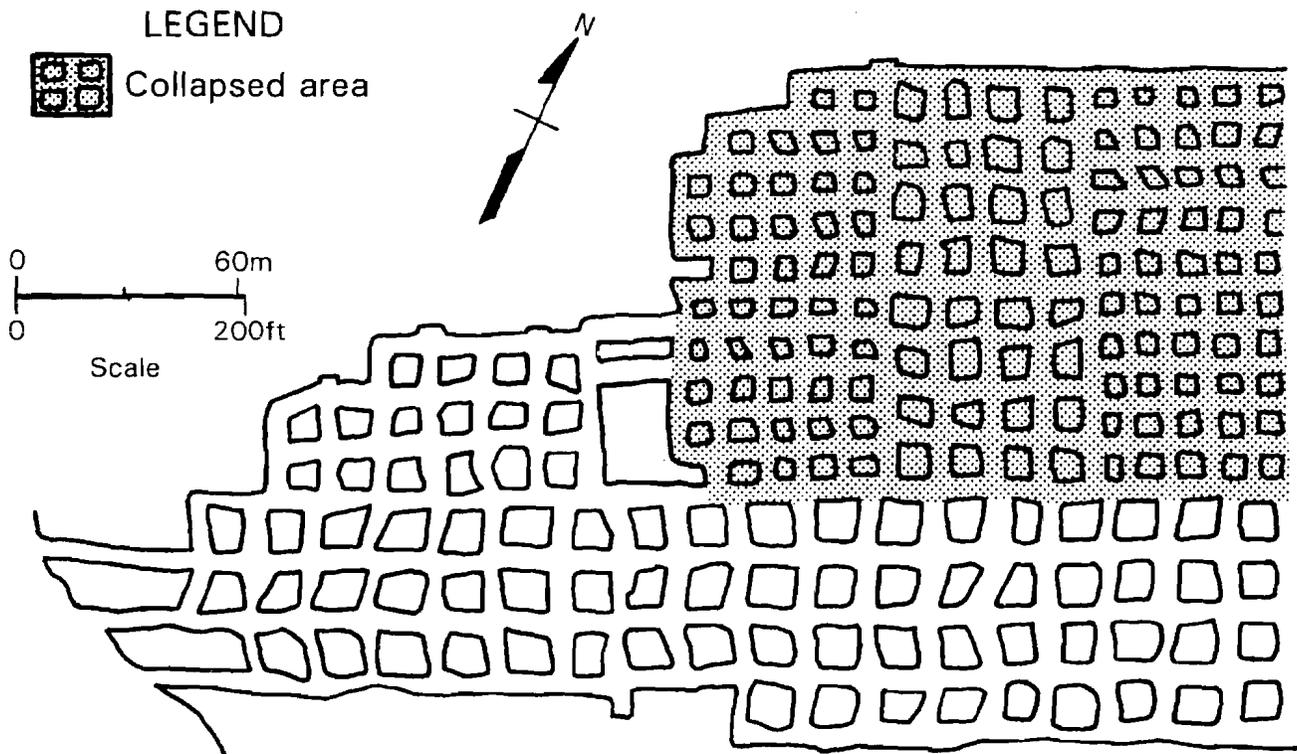


Figure 3.—Failed small-center development workings at Mine D.

FLOOR RECOVERY (MINE G)

Mine G is located in Utah and was extracting the 8-m (25-ft) thick Lower O'Connor Seam [Ropchan 1991]. There were previous workings in the Upper O'Connor above Mine G, separated by 18-23 m (60-80 ft) of overburden. The total overburden above the collapsed area was about 170 m (550 ft).

Room-and-pillar workings were advanced 2.4 m (8 ft) high on 18-m (60-ft) centers. The panel was developed nine entries wide and 535 m (1,740 ft) long. The pillars were not extracted on retreat, but an additional 3 m (10 ft) was removed from the floor, leaving 5.4-m (18-ft) high remnants. Mining the floor coal decreased the w/h ratio of the pillars from 5 to 2.2 and reduced their strength by about 45%.

The collapse occurred when the section was within two crosscuts of being completely retreated. The force of the airblast hurled three miners for distances of 12-30 m (40-100 ft), causing one severe head laceration. A 2-ton shop car was blown through a stopping. There was extensive damage to ventilation structures; concrete blocks from stoppings were scattered up to 30 m (100 ft). The main mine fan was stalled, and airflow in the mine was temporarily reversed. There was

some speculation that a north-south trending fault that bordered the panel may have contributed to the collapse.

SUMMARY OF CASE HISTORIES

Table 1 summarizes the mining dimensions of 13 examples of massive pillar collapses in U.S. coal mines. All occurred during the 1980's and 1990's, and all happened suddenly or without significant warning. Most resulted in airblasts and damage to the ventilation system.

Analysis of the data reveals some important similarities. First, the ARMPS SF was less than 1.5 in every case and less than 1.2 in 81% of the cases. This implies that the pillars were not sized to carry the full overburden load. Pillar failures are not unusual; however, most are slow and nonviolent. What apparently distinguishes the sudden collapses from the slow squeezes is the pillar's w/h ratio. Every massive pillar collapse involved *slender* pillars with a w/h ratio of less than 3. Another common characteristic of the collapses is that the overburden was judged to be relatively strong in every case. Finally, the collapsed areas were all at least 1.6 ha (4 acres), and the minimum dimension of a collapsed panel suffering major damage was 110 m (350 ft).

Table 1.—Massive pillar collapses in coal mines

Case history	State	Depth, m (ft)	Pillar size, m (ft)	ARMP SF	w/h ratio	Collapsed area, ha (acres)	Collapse size, m (ft)	Damage from airblast
A	WV	84 (275)	3 by 12 (10 by 40)	0.86	1.05	2.3 (5.7)	150 by 150 (500 by 500)	26 stoppings, 1 injury.
B1	WV	73 (240)	3 by 12 (10 by 40)	0.96	1.00	—	—	32 stoppings, fan wall out.
	WV		3 by 18 (10 by 60)	1.10	1.00			
B2	WV	75 (245)	3 by 12 (10 by 40)	0.94	1.00	1.7 (4.1)	100 by 150 (350 by 500)	40 stoppings.
B3	WV	85 (280)	9 by 9 (30 by 30)	1.46	3.00	2.8 (6.8)	180 by 180 (600 by 600)	70 stoppings.
	WV		6 by 12 (20 by 40)	1.47	2.00			
C1	WV	60 (195)	3 by 12 (10 by 40)	1.19	1.00	2.1 (5.2)	140 by 150 (450 by 500)	103 stoppings.
C2	WV	99 (325)	9 by 9 (30 by 30)	1.15	3.00	1.9 (4.8)	100 by 180 (350 by 600)	Minimal.
D	WV	69 (225)	6 by 6 (20 by 20)	1.15	1.82	1.7 (4.3)	100 by 160 (350 by 540)	37 stoppings.
	WV		9 by 9 (30 by 30)	1.42	2.73			
E1	WV	91 (300)	3 by 12 (10 by 40)	0.79	1.42	7.4 (18.2)	240 by 290 (800 by 950)	Major damage.
E2	WV	91 (300)	3 by 12 (10 by 40)	0.71	1.11	6.7 (16.6)	220 by 275 (720 by 900)	Major damage.
F	OH	76 (250)	2 by 12 (7 by 39)	0.66	2.12	2.0 (4.9)	90 by 215 (300 by 700)	Minimal.
G	UT	168 (550)	12 by 12 (40 by 40)	0.95	2.29	7.9 (19.4)	150 by 490 (480 by 1,620)	Major damage, 1 injury.
O	WV	—	—	1.03	2.50	1.8 (4.5)	120 by 150 (400 by 500)	—
R	CO	120 (400)	4 by 24 (12 by 80)	0.57	1.71	2.8 (6.8)	180 by 150 (600 by 500)	Minor damage.

NOTE.—Dash indicates no data available.

MECHANICS OF MASSIVE PILLAR COLLAPSES

A conceptual model of a massive pillar collapse can be described as follows. Undersized, regularly spaced remnant pillars help the stiff and competent roof to bridge a relatively wide span. A pressure arch is created, with much of the overburden load being transferred by the stiff roof to the barrier pillars surrounding the extraction area. Within the pressure arch, the pillars are shielded from the full weight of the overburden. Eventually, any one of a number of mechanisms may cause the pressure arch to break down:

- The extraction area becomes so large that it exceeds the bridging capacity of the roof.
- Mining approaches a fault or other discontinuity.
- The roof weakens over time.
- The remnant pillars weaken over time.

Once the pressure arch breaks down and additional overburden load is shifted to the pillars, their structural characteristics are such that a sudden, massive collapse can occur. Slender pillars have little residual strength and shed load rapidly as they fail. When one fails, the weight it transfers can overload adjacent pillars, and a rapid "domino" failure of adjacent pillars can ensue. Pillars that are more squat retain most of their load even after failure. Such pillars will squeeze slowly, rather than collapse.

Laboratory tests have shown that the residual strength of coal specimens depends on their w/h ratio [Das 1986]. Specimens with a w/h ratio of less than 3 typically have little residual strength, which means that they shed almost their entire load when they fail (figure 4). As the specimens

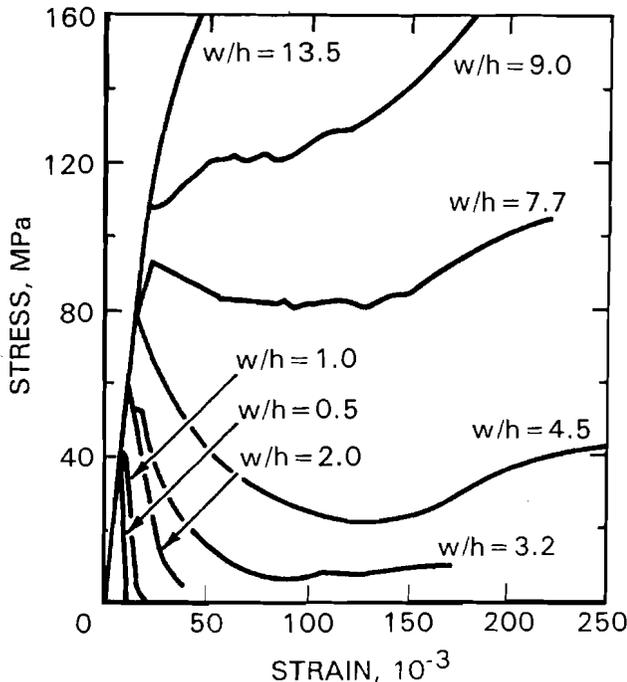


Figure 4.—Complete stress-strain curves for Indian coal specimens, showing increasing residual strength with increasing w/h ratio (after Das [1986]).

become more squat, their residual strength increases. Once the w/h ratio reaches 8-10, the specimens become "strain-hardening," which means that they never shed load, and sudden collapse is impossible.

Figure 5 summarizes available postfailure modulus data for large in situ coal specimens and full-scale coal pillars. The dashed line indicates a conservative envelope for these limited in situ data. In general, the laboratory postfailure moduli exceed the large-scale test values.

The importance of the postfailure stiffness is further explained by the theory of *local mine stiffness*, first proposed by Salamon [1970] and discussed by Zipf [1992, 1996]. The theory states that if the pillar's postfailure modulus (K_p) is less than the stiffness of the mine roof (the local mine stiffness, or K_M), the failure is stable and gradual (figure 6B). If K_p exceeds K_M , on the other hand, the failure is sudden and violent (figure 6A). The local mine stiffness depends on the modulus of the immediate roof; floor and pillar materials; and the layout of pillars, mine openings, and barrier pillars. The postfailure stiffness, K_p , depends on the w/h ratio of the coal pillar, as shown in figure 5. Using a boundary-element method program similar to the USBM's MULSIM/NL program, it is possible to simulate both massive pillar collapses and stable, progressive pillar failures [Zipf 1996]. The behavior of computer simulations changes depending on whether the model satisfies or violates the local mine stiffness stability criterion.

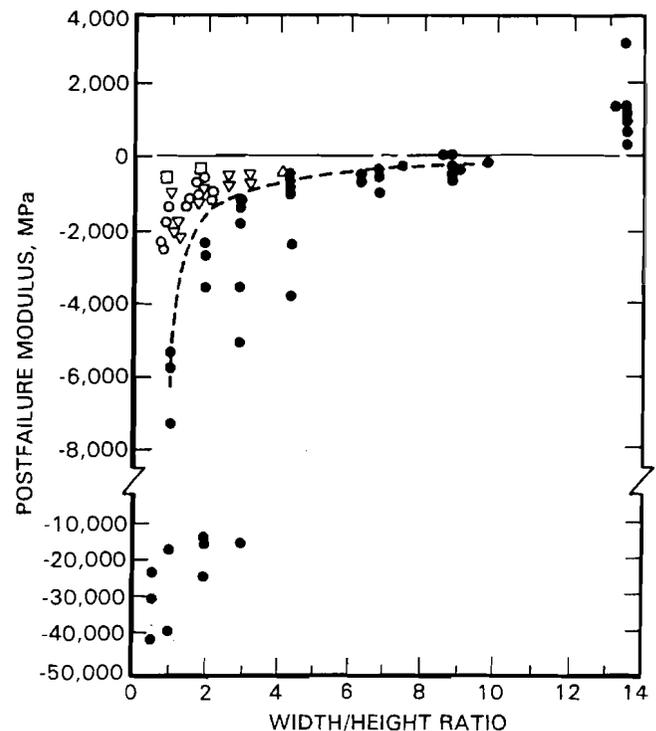


Figure 5.—Postfailure modulus of coal pillars, in situ coal specimens, and laboratory samples. Darkened circles represent laboratory tests, remaining symbols represent in situ tests [Chase et al. 1994].

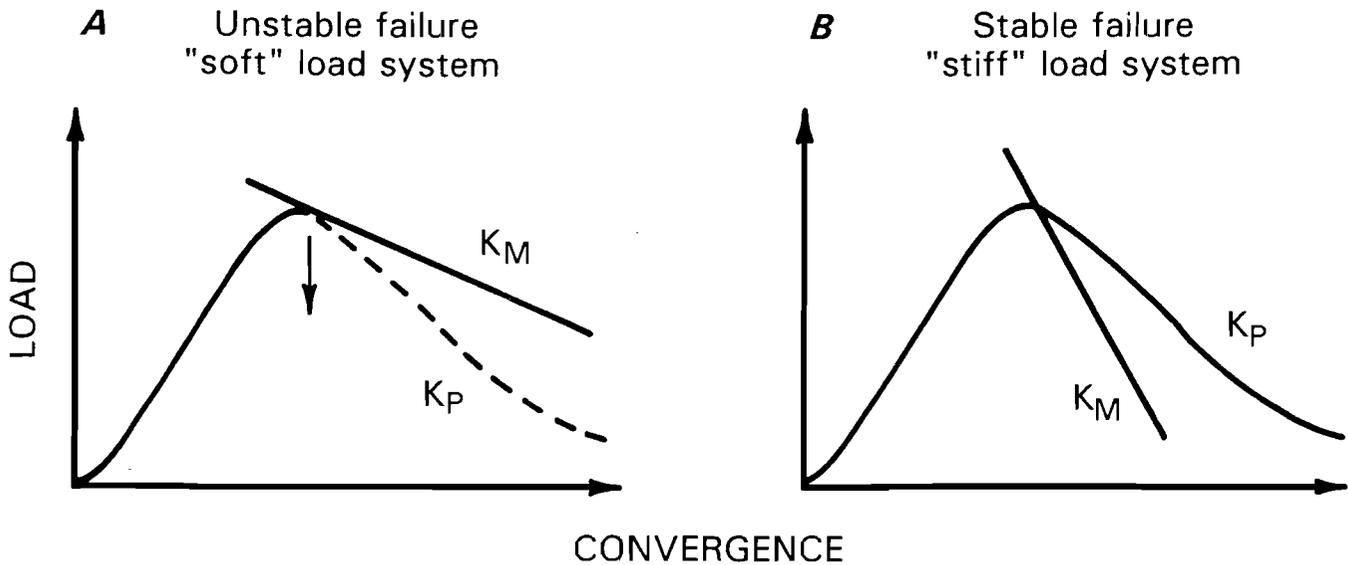


Figure 6.—Illustration of the local mine stiffness concept. A, local mine stiffness (K_M) is less than postfailure stiffness of the pillar (K_P), resulting in unstable failure. B, local mine stiffness (K_M) exceeds the pillar's postfailure stiffness (K_P), resulting in slow and stable failure.

DESIGN APPROACHES TO CONTROL MASSIVE PILLAR COLLAPSE

In coal mining, small-center mining and partial pillaring are methods to achieve high extraction without full pillar recovery. Both leave significant remnant pillars in the mined-out areas. For example, mining on 15-m (50-ft) centers using 6-m (20-ft) entries leaves about 35% of the coal in 9- by 9-m (30- by 30-ft) pillars. Splitting pillars developed on 18- by 18-m (60- by 60-ft) centers leaves about 22% of the coal. Both techniques can be adapted to avoid massive pillar collapses following the strategies of *prevention* or *containment*.

In the *prevention* approach, the panel pillars are designed so that collapse is highly unlikely. This can be accomplished by increasing either the SF of the pillars or their w/h ratio. In the *containment* approach, high extraction is practiced within individual compartments that are separated by barriers. The small pillars may collapse within a compartment; however, because the compartment size is limited, the consequences are not significant. The barriers may be true barrier pillars, or they may be rows of development pillars that are not split on retreat. The containment approach has been likened to the use of compartments on a submarine.

Full extraction can be another strategy to avoid massive pillar collapses. Mining all of the coal removes the support to

the main roof, thereby limiting the potential width of the pressure arch. Although some "first falls" behind longwalls and other full-extraction systems have been destructive, they generally involve areas smaller than massive pillar collapses.

SMALL-CENTER MINING: A PREVENTION APPROACH

Square pillars are generally used in small-center mining. Table 1 indicates that three collapses involved 9-m (30-ft) square pillars, and one involved 12-m (40-ft) square pillars. Square pillars may be designed to be collapse-resistant in two ways. The first is to increase their w/h ratio. Because no collapses have been documented in which the w/h ratio was greater than 3.0, a design w/h ratio of 4.0 is suggested to provide an adequate margin of safety.

Pillar collapses may also be avoided by maintaining a sufficiently high SF. The ARMPS case history data base [Mark and Chase 1997] suggests that normally an ARMPS SF of 1.5 is sufficient to limit the probability of pillar failure. Where slender pillars are being employed and their failure may result in a massive collapse rather than a slow squeeze, it

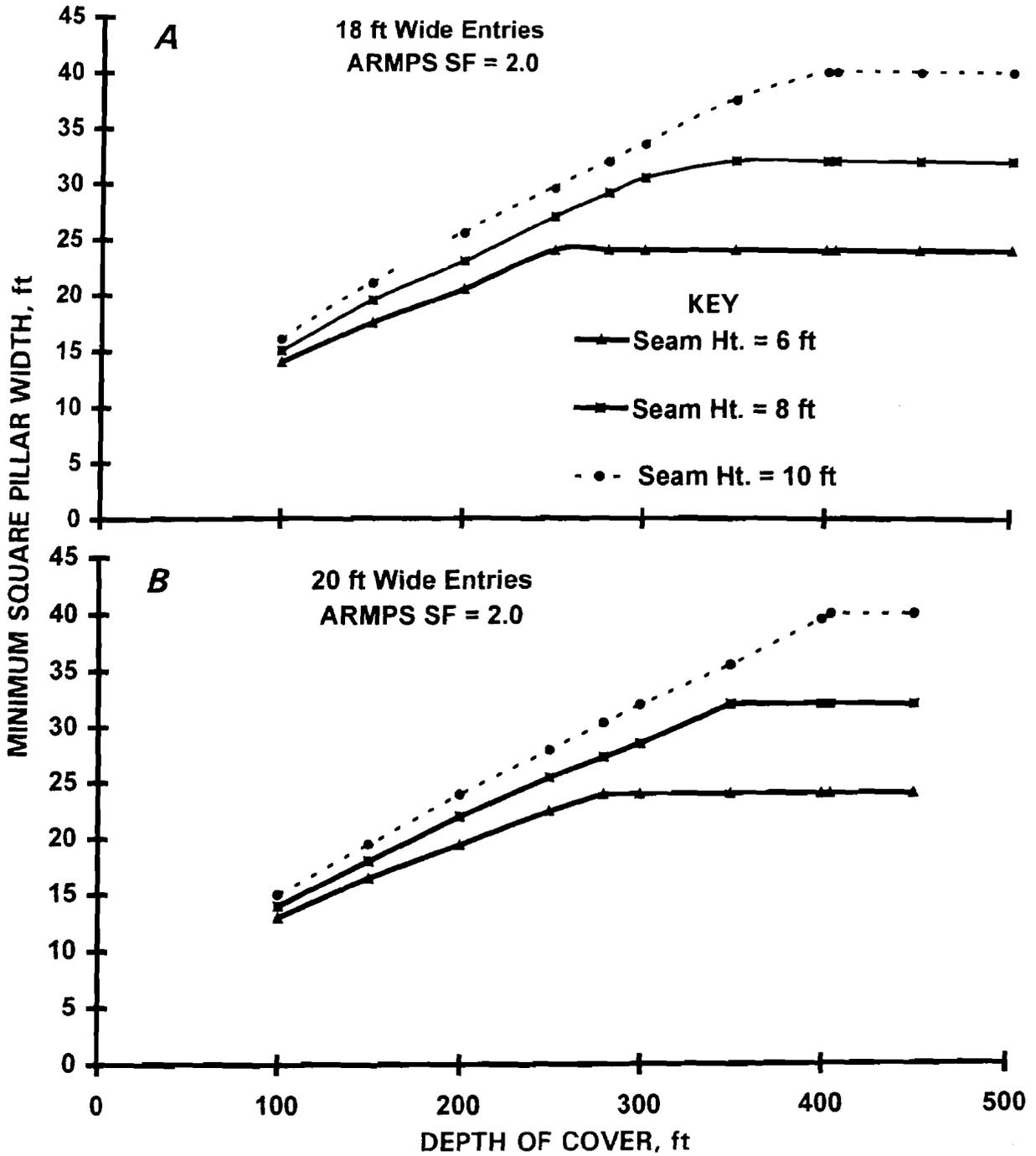


Figure 7.—Suggested minimum square pillar size to avoid massive pillar collapse. A, 5.5-m (18-ft) entries; B, 6-m (20-ft) entries.

might be prudent to increase the SF to 2.0. The SF can be increased by increasing the pillar width, decreasing the extraction ratio, or both. These two design criteria have been combined to develop guidelines for small-center mining. Figure 7 was developed assuming square pillars with an SF of 2.0 or a w/h ratio of 4.0.

When using 6-m (20-ft) wide entries, the minimum suggested pillar sizes are increased by about 6%. Also note that these design criteria are only for controlling massive pillar collapses. At greater depths, pillar sizes may need to be increased beyond a w/h ratio of 4 to maintain an adequate SF. The failure of pillars with a w/h ratio greater than 4 should be a slow squeeze rather than a sudden collapse.

PILLAR SPLITTING: A CONTAINMENT APPROACH

Fenders left from pillar-splitting operations have failed at even shallow depths. For example, 3- by 12-m (10- by 40-ft) fenders in a 3-m (10-ft) seam have an SF of 1.5 at only 55 m (180 ft) of cover. The potential for a destructive massive collapse can be reduced by limiting the size of the gob area. To separate the gob areas, rows of unsplit development pillars can be left as barriers. This strategy is based on two assumptions:

- By limiting the span above the mined-out area, a bridging failure of the strong overburden is less likely.
- By minimizing the size of the potential collapsed area, any airblast resulting from a collapse would be less powerful.

Table 1 shows that no major collapses have been documented in which the gob area was less than 1.5 ha (4 acres). In the five cases where the gob area was between 1.5 and 1.9 ha (4 and 5 acres), about 60% of the incidents resulted in major damage. Additionally, no damaging incidents occurred when the minimum dimension of the mined-out area was less than 100 m (350 ft). Using these data, acceptable dimensions of a pillar-splitting operation might be a maximum area of 1.2 ha (3.2 acres), with a minimum dimension of less than 90 m (300 ft). For example:

- Assuming 18- by 18-m (60- by 60-ft) centers in a nine-entry system with four rows split, the mined-out area would

have a minimum dimension of 72 m (240 ft) and an area of about 1.1 ha (3 acres), as shown in figures 8A and 8B.

- Assuming the same pillar size in a six-entry system with five rows split, the minimum dimension would be 90 m (300 ft) and the area would be about 1 ha (2.5 acres), as shown in figures 8C and 8D.

The next question is: how many unsplit rows should be left between these mined-out areas? The goal is to leave enough of a "barrier" so that the failure of one gob area does not initiate failure in adjacent areas. ARMPS was used to evaluate the loading on unsplit pillars between two mined-out areas. The program was modified so that two "front" gobs could be applied to the unsplit pillars. The analyses were run with abutment angles of 90°, which assumes that none of the load is carried by the gob, but instead is transferred to the barriers.

In the first set of analyses, two rows of full-sized pillars were used as the barrier. An ARMPS SF of 1.5 was deemed necessary to prevent the collapse of one gob area triggering the collapse of an adjacent area. Three rows of pillars were used in the second set of analyses; the SF was reduced to 1.0 because of the greater stiffness of the barrier. Pillars on 18- by 18-m (60- by 60-ft) centers were used in all cases.

Other parameters that were varied included the number of rows that were split (three, four, and five), the entry width (5.5 and 6 m (18 and 20 ft)), the seam height (2, 2.5, and 3 m (6, 8, and 10 ft)), and the number of entries in the section (five, seven, and nine). The results are presented in figure 9, which shows the suggested maximum depth of cover for each combination of parameters. In general, considering 5.5-m (18-ft) entries in a 2.5-m (8-ft) seam, it appears that two rows of unsplit pillars are an adequate barrier at depths less than about 300 ft and that three rows are acceptable to about 170 m (550 ft) of cover.

Barriers must also be left between extracted panels. These can be unsplit development pillars or solid coal. If unsplit development pillars are used, the analysis in figure 9 should apply. For solid coal barriers, figure 10 shows the suggested widths, using the same loading assumptions. For a 2.5-m (8-ft) seam, a 17-m (55-ft) solid barrier appears to be appropriate at 75 m (250 ft) of cover, and 23 m (75 ft) might be needed at 120 m (400 ft).

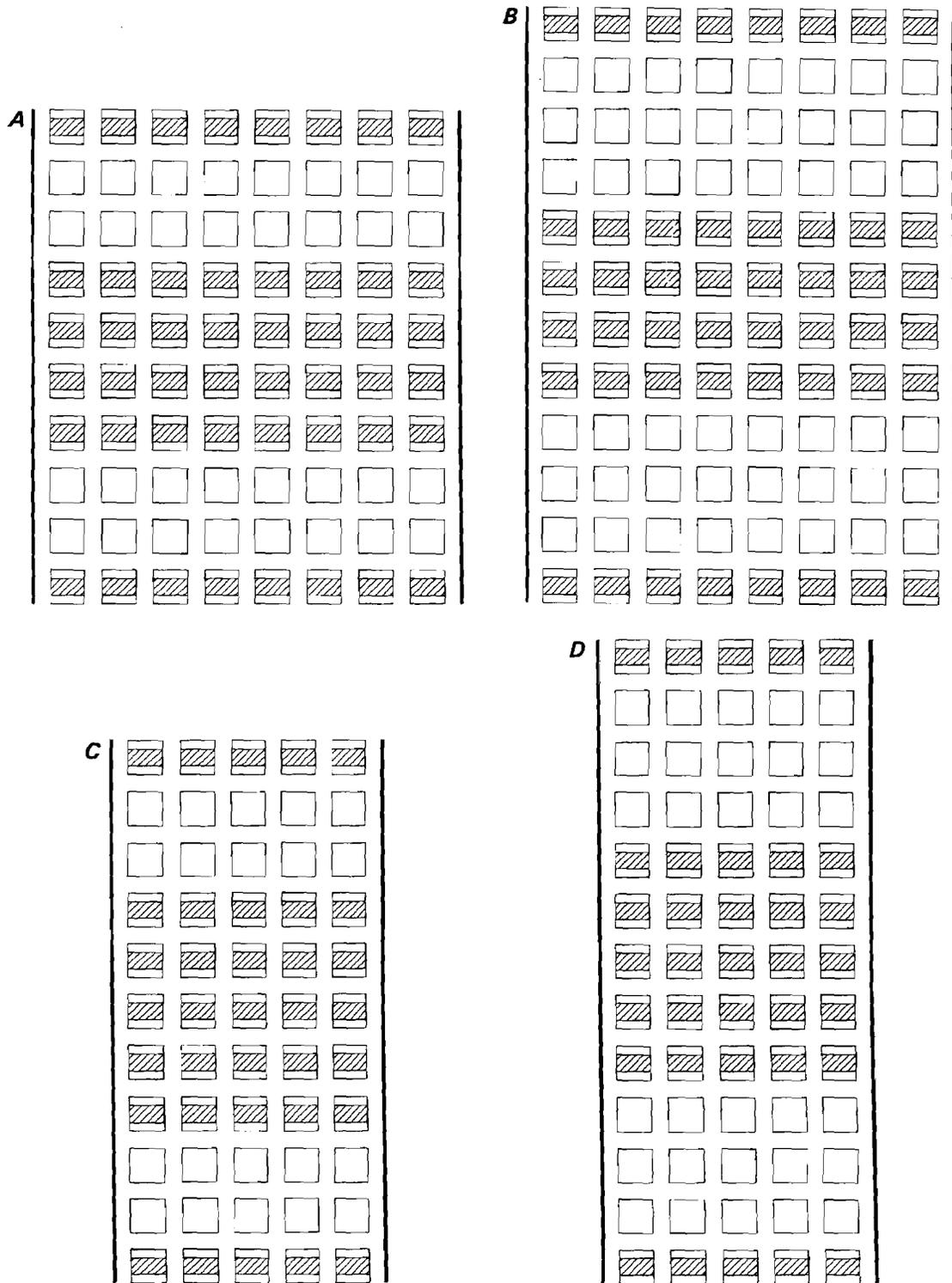


Figure 8.—Possible pillar-splitting plan for airblast control. A, nine-entry system, two rows of unsplit pillars for barrier. B, nine-entry system, three rows of unsplit pillars for barrier. C, six-entry system, two rows of unsplit pillars for barrier. D, six-entry system, three rows of unsplit pillars for barrier.

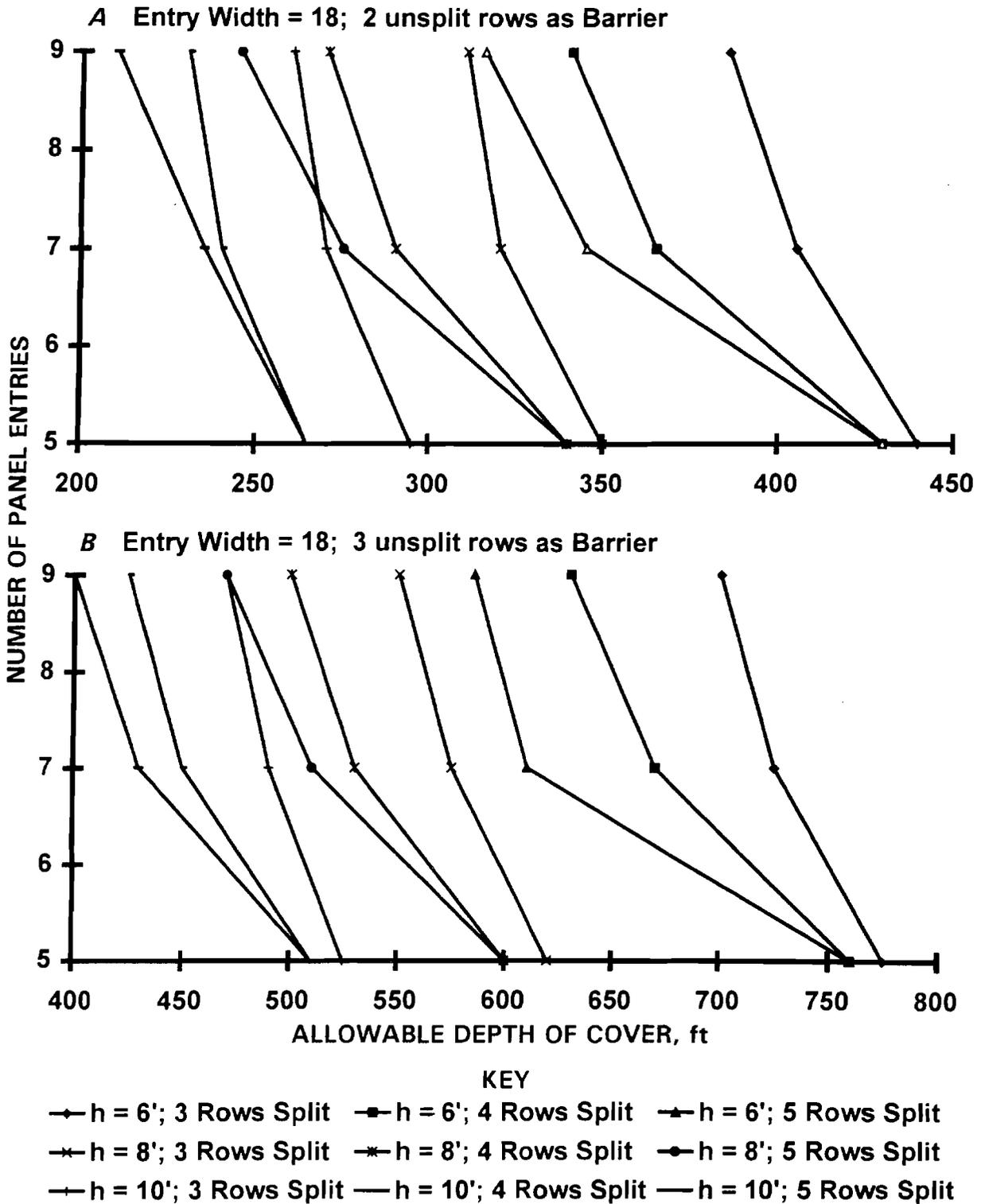


Figure 9.—A, suggested maximum depth for two rows of unsplit pillars as barrier between gob areas, 5.5-m (18-ft) entry, 18-by 18-m (60- by 60-ft) pillars. B, suggested maximum depth for three rows of unsplit pillars as barrier between gob areas, same entry and pillar sizes.

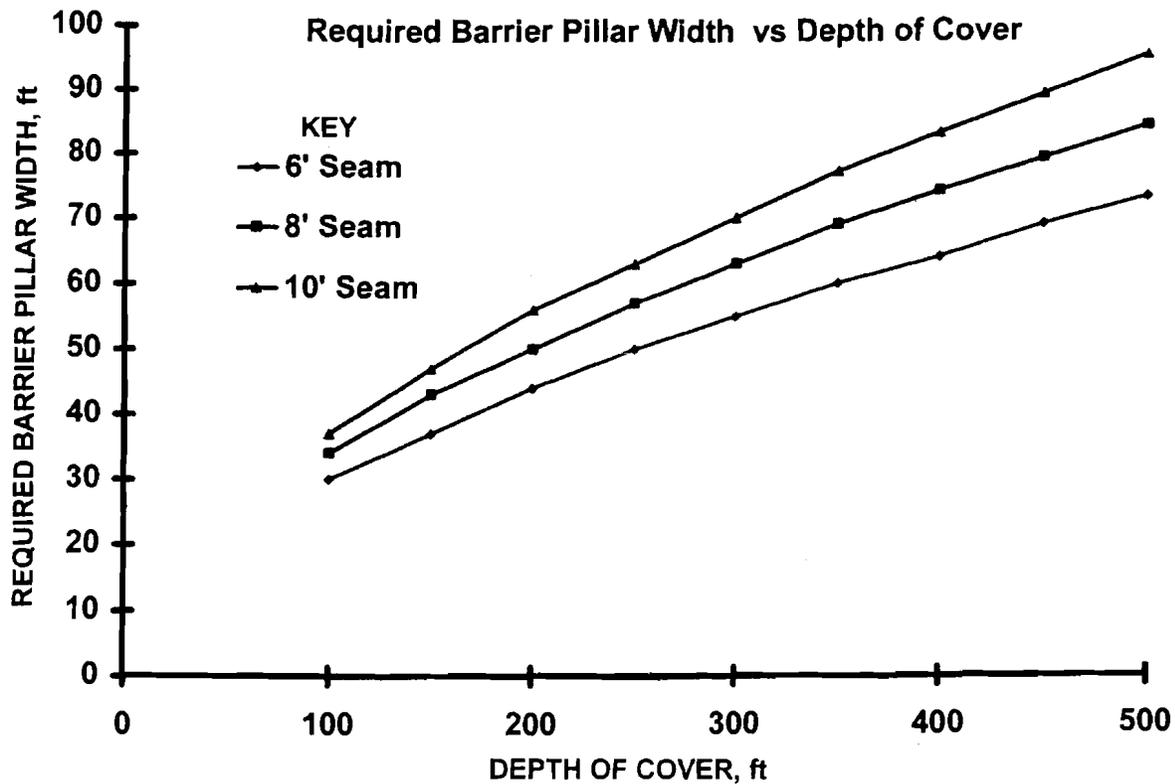


Figure 10.—Suggested solid coal barrier width between two areas where pillars have been split.

CONCLUSIONS

The potential for massive pillar collapses should always be considered when designing room-and-pillar mining operations. A collapse can occur when one pillar fails suddenly, overstresses its neighbors, causing them to fail, and so forth, in very rapid succession. Very large mining areas can collapse via this mechanism within seconds with little or no warning. The collapse itself can pose serious danger to nearby mining personnel. Additionally, the collapse can induce a violent airblast that disrupts or destroys the ventilation system. Further critical danger to miners exists if the mine atmosphere becomes explosive or contaminated as a result of the pillar collapse.

Research has found that massive collapses in coal mines have the following common characteristics:

- Slender pillars (w/h ratio less than 3.0).
- Low SF (less than 1.5).
- Competent roof strata.
- Collapsed area greater than 1.6 ha (4 acres).
- Minimum dimension of the collapsed areas greater than 110 m (350 ft).

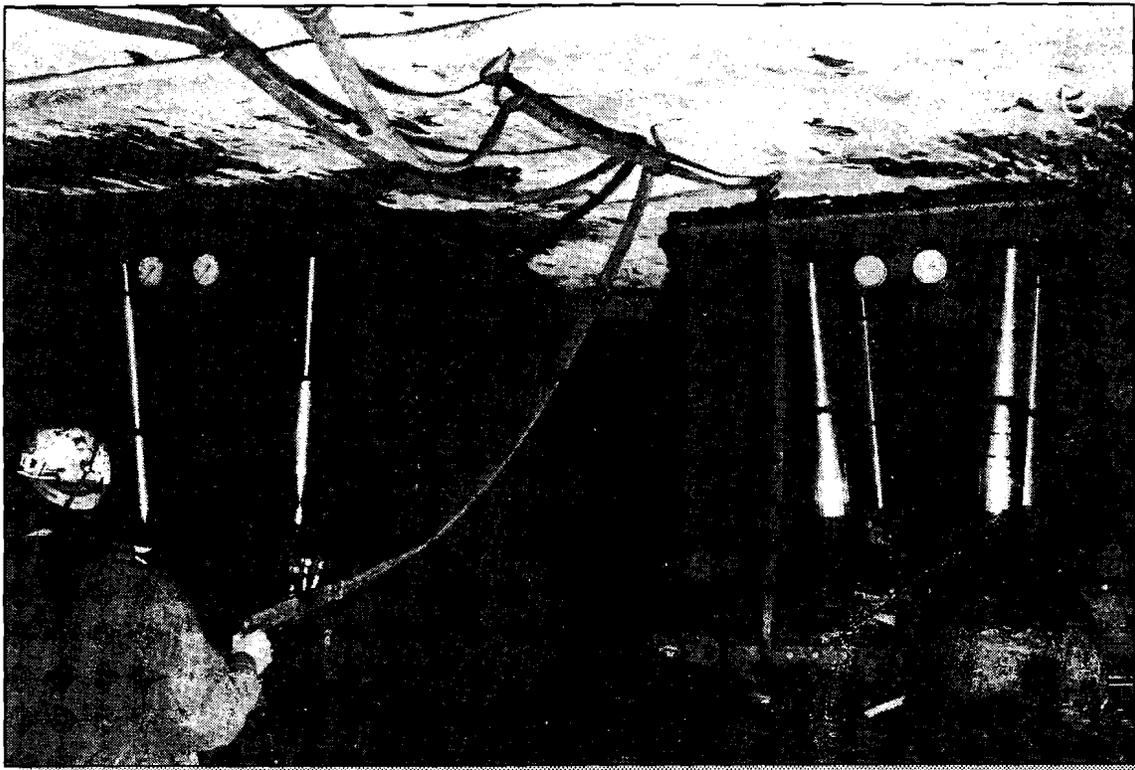
Two alternative strategies may be successful in preventing massive pillar collapses. For small-center mining, *prevention* may be applied by increasing either the w/h ratio or the SF. *Containment* is appropriate for pillar splitting and requires leaving barriers or rows of unsplit pillars to limit the area of potential collapses. A final strategy is to go to full pillar extraction. By removing the support provided by the remnant fenders left during traditional pillar splitting, the bridging capacity of the roof should be substantially reduced.

Finally, it is important to note that the massive pillar collapses discussed in this paper are not to be confused with coal bumps or rock bursts. Although the outcomes may appear similar, the underlying mechanics are entirely different. Bumps are sudden, violent failures that occur near coal mine entries and expel large amounts of coal and rock into the excavation [Maleki 1995]. They occur at great depth, affect pillars (and longwall panels) with large w/h ratios, and are often associated with mining-induced seismicity. The design recommendations discussed here for massive pillar collapses do *not* apply to coal bump control.

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Cover photo: Pillar extraction using mobile roof supports.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	lbf	pound (force)
ft	foot	m	meter
ft/min	foot per minute	m/min	meter per minute
ft ²	square foot	m ²	square meter
ft ³	cubic foot	m ³	cubic meter
GPa	gigapascal	min	minute
ha	hectare	mm	millimeter
in	inch	MPa	megapascal
in ²	square inch	psi	pound (force) per square inch
kg	kilogram	st	short ton
kips/in	kips per inch	st/h	short ton per hour
kN	kilonewton	t	ton (metric)
kN/cm	kilonewton per centimeter	%	percent
kPa	kilopascal	°	degree
lb	pound		

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