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Preventing Roof Fall Fatalities During Pillar Recovery: A Ground Control Success Story

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ABSTRACT

For decades, pillar recovery accounted for a quarter of all roof fall fatalities in underground coal mines. Studies showed that a miner on a pillar recovery section was at least three times more likely to be killed by a roof fall than other coal miners. Since 2007, however, there has been just one fatal roof fall on a pillar line. This paper describes the process that resulted in this historic achievement. It covers both the key research findings and the ways in which those insights, beginning in the early 2000s, were implemented in mining practice.

One key finding was that safe pillar recovery requires both *global* and *local* stability. Global stability is addressed primarily through proper pillar design, and became a major focus after the 2007 Crandall Canyon mine disaster. But the most significant improvements resulted from detailed studies that showed that local stability, defined as roof control in the immediate work area, could be achieved with three interventions:

- Leaving an engineered final stump, rather than extracting the entire pillar;
- Enhancing roof bolt support, particularly in intersections, and
- Increasing the use of Mobile Roof Supports (MRS)

A final component was an emphasis on better management of pillar recovery operations. This included a focus on worker positioning, as well as on the pillar and lift sequences, MRS operations, and hazard identification. As retreat mines have incorporated these elements into their Roof Control Plans, it has become clear that pillar recovery is not "inherently unsafe."

The paper concludes with a discussion of the challenges that remain, including the problems of rib falls and coal bursts.

INTRODUCTION

Pillar recovery has always been an integral part of underground coal mining in the US. When room-and-pillar methods are employed, large blocks of coal in the form of pillars are initially left in place to support the weight of the overburden. Unless these pillars are subsequently recovered, the coal they contain will never be mined.

During the retreat mining process the roof above the worked-out area caves and the overburden subsides (Figure 1). Because premature caving can cause hazardous roof falls while the miners are still present, pillar recovery has historically been less safe than other underground mining methods. Rice (1916) found that of 317 miners that were killed by roof falls in one year in Pennsylvania, 98 perished while attempting to recover pillars. He concluded "Drawing pillars is plainly most dangerous work."

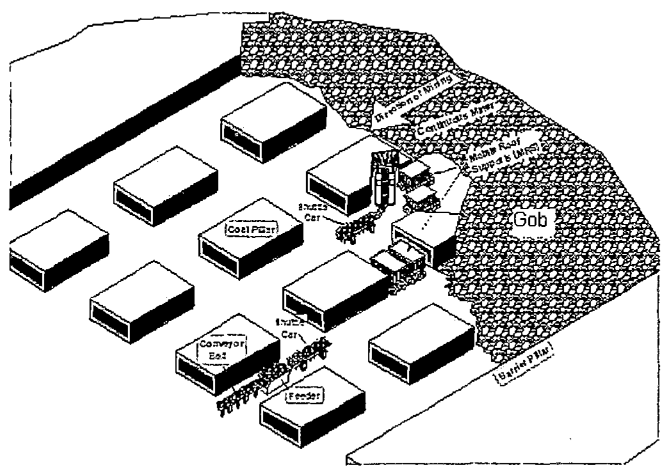

Figure 1. Retreat phase of room-and-pillar mining showing pillar recovery. The gob is the area where the pillars have been extracted and the roof has caved.

DEMOGRAPHICS OF PILLAR RECOVERY

No official statistics are available on the prevalence of retreat mining. Indeed, collecting such data would be difficult, since many mines switch back and forth from development to retreat mining. Fortunately, through the years a number of "snapshots" have been taken of the retreat mining segment of the industry.

Kauffman et al. (1981) developed a retreat mining manual which included a survey of roof control plans from all over the US. They found that out of the 4166 underground coal mines operating during the late 1970's, 1093 (26%) included pillar recovery in their roof control plans. The regions with highest rates of retreat mining plans were PA (pillar extraction included in 70% of plans), Northern WV (60%) and the Western US (56%). In the Central Appalachia coalfields, which cover Southern WV, Eastern KY, Western VA, and Northeastern TN, only 23% of the roof control plans included pillar recovery. But because there were so many mines located in Central Appalachia, a large majority (79%) of all US retreat mines were located there. Kauffman et al. (1981) made no attempt to determine the production or the number of miners at the pillar recovery mines.

A NIOSH study (Mark et al., 1997) made use of a 1993 MSHA survey of gob ventilation and bleeder systems in US underground mines (Urosek et al., 1995). The MSHA survey found that 367 non-longwall mines had gob areas, about evenly split between "active" and "inactive" gob areas. The NIOSH study linked only the mines with active gob areas to the MSHA Accident and Employment Data Base, and found that they employed 9,100 miners and produced 61.7 million tons, while the totals for all room and pillar mines were 33,100 miners and 214.3 million tons. NIOSH also found that about two-thirds of the active retreat mining was taking place in Central Appalachia, with some of the remainder coming from every other coalfield except Western KY. However, the NIOSH study significantly underestimated the total size of the retreat mining sector because it excluded the mines with inactive gobs. A mine was not counted unless it was actively extracting pillars at the moment the MSHA survey was conducted, even if it contained inactive gobs and was developing pillars for later extraction. In particular, small single-section mines in Central Appalachia were probably underrepresented.

A few years later, NIOSH surveyed MSHA Roof Control Specialists about the pillar recovery practices in the mines they inspected (Mark et al., 2003). The data was again linked to the MSHA Accident and Employment Data Base. This study found that in 2001, 370 retreat mines produced 108 million tons of coal, about two-thirds of the total non-longwall underground production. At this time more than 90% of the retreat mine production came from Central Appalachia, with about 9% coming from Northern West Virginia. There was essentially no pillar recovery taking place in the Midwest or in Alabama.

Pillar extraction waned rapidly in Northern Appalachia after 2001. In recent years the total number of retreat mines anywhere outside of Central Appalachia can be counted in single digits.

While retreat mining has largely disappeared from the other coalfields, the 2003 NIOSH survey found that in Central Appalachia mines that practiced pillar extraction accounted for about 75% of the non-longwall production in the region. A 2015 survey of MSHA Roof Control Supervisors confirmed that ratio was still valid. So while no precise data on retreat mining has been collected since 2001, data from all Central Appalachian room and pillar mines can be considered a good proxy for the pillar recovery sector of the US underground coal industry.

Figure 2 shows that Central Appalachian room and pillar production declined slowly between 2001 and 2011, from 108 to 82 million tons. During this same period, however, productivity also declined, from 3.12 to 1.59 tons per worker hour. Therefore, the number of miners exposed to pillar recovery likely *increased* during this period, peaking in 2011 (Figure 3). NIOSH estimated in 2001 that about 10% of all underground hours were engaged in pillar recovery, and this estimate was probably valid through 2011. The number of both mines and miners in Central Appalachia has greatly declined since then.

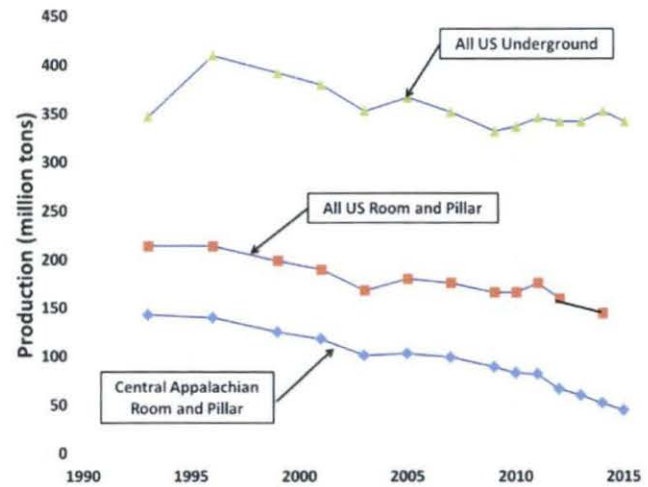

Figure 2. Trends in US underground coal production, 1993-2015 (source: Energy Information Agency (2015)).

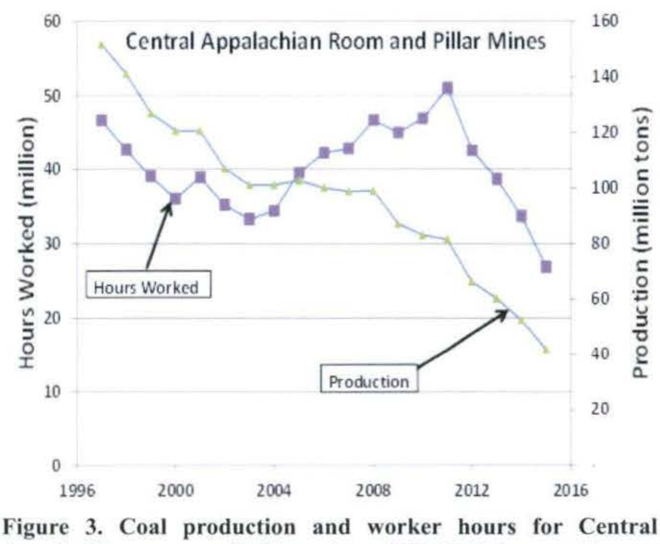

Figure 3. Coal production and worker hours for Central Appalachian room-and-pillar mines, 1993-2015 (source: Energy Information Agency (2015)).

GROUND FALL FATALITIES DURING PILLAR RECOVERY

Retreat mining has long been considered the most hazardous type of underground mining. During the first decade of the 2000's, three separate studies on the safety of pillar recovery were commissioned by the state of WV (McAteer, 2001), the State of KY (Marshall Miller and Associates, 2006), and by the US Congress (NIOSH, 2010).

Historically, roof falls have been the most significant hazard faced by miners on pillar recovery sections. Montague (1988) found that between 1978 and 1986, out of 328 total roof fall fatalities, 67 (20%) were associated with pillar recovery. For the period 1989 to 1996, Mark et al. (1997) found that out of a total of 111 roof and rib fatalities, 33 (30%) took place during pillar recovery. Mark et al. (2003) estimated that a coal miner on a pillar recovery section was approximately three times more likely to be fatally injured in a roof fall than a miner on an advancing section.

In recent years, the number of roof falls during pillar recovery has been dramatically reduced, however. As shown on Figure 4, there has been just one roof fall fatality in the eight years since 2007. This compares to a total of 19 in the prior decade. Since the total exposure to retreat mining has only recently fallen,[1] it seems that a retreat miner's risk of being killed by a roof fall was reduced by a factor of 16. The focus of this paper is on how this historic improvement was achieved.

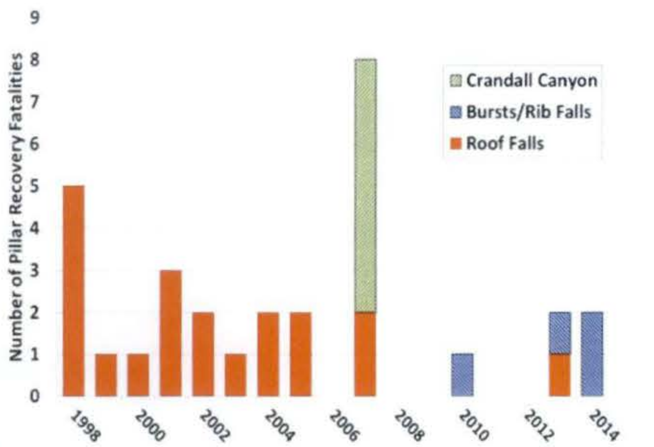

Figure 4. Ground fall fatalities during pillar recovery, 1998-2015.

Unfortunately, roof falls are not the only hazard faced by miners engaged in pillar recovery. The 2007 Crandall Canyon Mine Disaster, which was caused by a pillar collapse, initially cost six miners their lives, and then three additional miners were killed during the rescue attempt. In 2010 one retreat miner was killed in a rib fall, and three miners were killed by two separate coal burst incidents in 2013 and 2014. Each of these hazards will be discussed as well.

Previous studies have found that the roof/rib non-fatal injury rate has been slightly lower in pillar recovery mines than it is in other room and pillar mines (Mark et al., 1997; Mark et al. 2003). The explanation was that while the process of bolting freshly-exposed mine roof is normally a major source of rock fall injuries, retreat mining typically requires relatively little roof bolting. However, NIOSH (2010) found that the subset of deep-cover retreat mines (cover greater than 1000 ft), had a much greater *rib fall* non-fatal injury rate than other mines. During the period 2006-2008, nearly one-quarter of all the rib fall injuries in the entire U.S. underground coal industry occurred in the small group of deep cover retreat mines that accounted for less than 10% of all hours worked underground.

ROCK MECHANICS OF PILLAR RECOVERY

Throughout much of the 20[th] century, mining engineers had a relatively simple understanding of the rock mechanics involved in pillar recovery. This traditional theory was expressed clearly in the 1973 edition of the SME Mining Engineering Handbook:

"As complete recovery as possible is the No. 1 goal in pillar mining. Nothing should be left large enough to prevent proper caving and subsidence of the roof, which should follow immediately or very shortly after mining of each final stump. If necessary, posts and cribs should be removed, stumps shot as needed and other steps taken as required to insure proper caving and minimum transfer of weight to the mineral being mined. In extreme circumstances, this may involve drilling and shooting the overlying material to induce caving....Among the hazards and handicaps of roof hanging up on pillars or supports left in the gob are squeezing and crushing of the coal or other material or complete collapse at some point in the mining process, endangering men and equipment and causing loss of mineral."

One result of the traditional emphasis on complete extraction was the large number of miners killed while extracting the final pushout stump (Figure 5). Montague (1988) found that 50% of the 67 retreat mining fatalities he analyzed occurred during the mining of the pushout. Similarly, Mark et al. (1997) found that final stumps accounted for 45% of the 26 retreat mining fatalities between 1989 and 1996. These numbers are particularly staggering when one considers that only a small fraction of the total time spent during pillar recovery is devoted to the pushout extraction.

Figure 5. A final stump.

When Mark and Zelanko (2005) analyzed MSHA fatality reports from 25 pillar recovery incidents that occurred between 1992 and 2005, they found that two-thirds of the mines where the fatalities had occurred had been following their approved Roof Control Plans. In other words, the plans themselves were inadequate, not the implementation. Since the traditional emphasis on total recovery was providing designs, procedures, and practices that were insufficient to protect miners, a new paradigm was needed.

1 For the ten-year period 1998-2007, DOE statistics show that an average of 38.44million hours were worked each year in Central Appalachian room and pillar mines. For the eight-year period 2008-2015, the annual average was 41.44 million hours. Therefore, there was one roof fall fatality during pillar recovery for every 20 million hours worked in decade prior to 2008, and one for every 331 million hours in the eight years since.

The new risk reduction strategy for pillar extraction developed by Mark and Zelanko (2005) included three components:

- **Global Stability**: Prevention of section-wide pillar failure.
- **Local Stability**: Prevention of roof falls in the working area.
- **Work procedures and worker location**: Minimizing exposure to hazardous areas.

During the past decade, these new concepts have been incorporated into Roof Control Plans for pillar recovery, with dramatic results. The MSHA (2013) Roof Control Plan Review and Approval Handbook reflects the new approach, and contains guidance documents and checklists that have been developed regarding retreat mining safety.

GLOBAL STABILITY

Proper pillar design is the key to ensuring global stability, because the pillars normally carry the weight of hundreds, or even thousands, of feet of overlying rock. In contrast, artificial supports like roof bolts or posts can carry just a few feet of rock, and so can only provide local stability to the roof directly above the miners. Without global stability, no local support strategy can be effective.

Mining engineers have known about the need for proper pillar sizing for more than a century. For example, Bunting (1911) wrote that "to mine without leaving adequate pillar supports will result, sooner or later, in a squeeze." Unfortunately, pillar design remained more of an art than a science for most of the 20th century. In particular, none of the popular empirical techniques considered the effect of the abutment loads generated by pillar extraction on the pillar line.

The 2007 Crandall Canyon Mine Disaster was a tragic reminder of the importance of global stability. The MSHA (2007) report on the disaster concluded that "it was obvious, at the most fundamental level, that the accidents at Crandall Canyon Mine were precipitated by pillar failures." The report further cited the "flawed pillar design" which allowed the stress level to "exceed the strength of a pillar or group of pillars near the pillar line," resulting in a local failure that triggered a widespread collapse.

Fortunately, reliable techniques for designing coal pillars are now readily available. The Analysis of Retreat Mining Pillar Stability (ARMPS) is the most widely used pillar design method in the U.S. ARMPS is an empirical method that was originally developed by NIOSH in the mid-1990s (Mark and Chase, 1997). Statistical analysis was used to derive design guidelines that separate the "successful" case histories (those where the entire panel was mined without pillar failure) from those that were "unsuccessful."

The original ARMPS database consisted of approximately 150 case histories, representing a broad range of cover depths. A follow-up study that focused on deep cover pillar recovery (Chase et al., 2002) added 100 case histories from mines in central Appalachia and the West where the depth of cover exceeded 750 ft. After Crandall Canyon, a further 400 case histories were added to the ARMPS database.

The latest version of ARMPS features a "pressure arch" loading model and new criteria for sizing the barrier pillars between panels (Mark, 2010). Where a retreat mine may be impacted by a multiple seam mining (an all-too-common situation in Central Appalachia), the NIOSH program Analysis of Multiple Seam Stability (AMSS) is available to assist with pillar design (Mark, 2007).

The LaModel program can also be used for coal pillar design (Heasley, 1997). LaModel is a numerical model that can analyze more complex mining geometries, accounting for such factors as multiple seam interactions and variable surface topography. LaModel is unique in that it includes "laminations" allowing it to more accurately simulate the behavior of layered, sedimentary overburden. It has also been extensively calibrated to case histories (Heasley et al., 2010).

MSHA's standard at 30 CFR 75.203 (a) states that "[p]illar dimensions shall be compatible with effective control of the roof, face and ribs and coal or rock bursts." In the wake of the Crandall Canyon disaster, MSHA distributed a series of Program Information Bulletins (PIBs) and other documents that described the technical and engineering data related to pillar design that mine operators must submit as part of their Roof Control Plans (Stricklin, 2008a; Stricklin, 2008b; Stricklin and Skiles, 2008; Skiles and Stricklin, 2008). Subsequently, MSHA (2013) issued its Roof Control Plan Review and Approval Handbook ("the Handbook") which states that "in order to comply with 30 CFR 75.203 (a), the retreat mining portion of the roof control plan submittal should include an engineering design and supporting analysis."

The widespread application of pillar design based on engineering principles to retreat mining has apparently resulted in a dramatic reduction in the number of squeezes, wide spread propagating ground failure, and other types of pillar failures. While no official statistics are available, the sheer number of failures included in the ARMPS and AMSS data bases attests to the prevalence of such events in the past. In contrast, in recent years only a handful of pillar failures have come to the attention of MSHA Technical Support.

In retrospect, it seems likely that most of the squeezes that occurred in past decades were due to undersized pillars, not to poor caving. Miners who experienced a squeeze in those days wanted an explanation, and "incomplete extraction" was a convenient culprit. As discussed below, today large remnants are almost always purposely left standing, and it is not unusual for the roof to stay up for some time after a pillar is fully extracted. Yet the incidence of squeezes has diminished, not increased. In fact, our modern understanding of the overburden load distribution associated with full extraction mining indicates that the traditional theory was based on a misconception. The height of an immediate roof cave is so small compared to the total weight of the overburden, and the stiffness of the freshly created gob is so low, that it is hard to see how the caving of the immediate roof could seriously affect the overburden loads carried by the pillars.[2]

2 Consider, for example, a seven-entry pillar extraction section with a six foot mining height under 1000 feet of cover. If the pillars are developed on 60 by 80 foot centers with 20 foot wide entries, and the NIOSH default value of 21 degrees is used for the abutment angle, then the ARMPS SF is 1.35. Increasing the abutment angle to 90 degrees, which reduces the load carried by the gob to zero, decreases the ARMPS SF only to 1.28. In other words, for this panel geometry, going from "normal" caving to no caving at all increases the total pillar load by less than 5%.

LOCAL STABILITY RISK FACTORS

Global stability is a necessary, but not sufficient, condition for creating a safe working area. Local stability depends on providing adequate support to the immediate roof. The crucial area is the *active intersection* just outby the pillar being extracted. Mark and Zelanko (2005) identified three key technologies for improving the level of roof support during pillar recovery:

- Leaving an engineered final stump, rather than extracting the entire pillar;
- Substituting mechanized Mobile Roof Supports (MRS) for traditional wood timbers;
- Using longer and stronger roof bolts on retreat sections, particularly in intersections.

Over the past decade, concerted efforts have been made to implement these technologies into retreat mining practice and approved roof control plans, and they are discussed in Appendix G of the Handbook (MSHA, 2013).

Final Stump: Leaving the final stump is perhaps the biggest change with the new paradigm. Rather than viewing the stump as a hindrance to "necessary" caving, the stump is now seen as an essential roof support. A 2013 survey of Roof Control Supervisors in the five Central Appalachian MSHA Districts found that 98% of retreat mining roof control plans now leave a final stump in place. In some cases these stumps are as small as six by six feet, but they are more commonly at least eight by eight feet (Figure 6 part a).

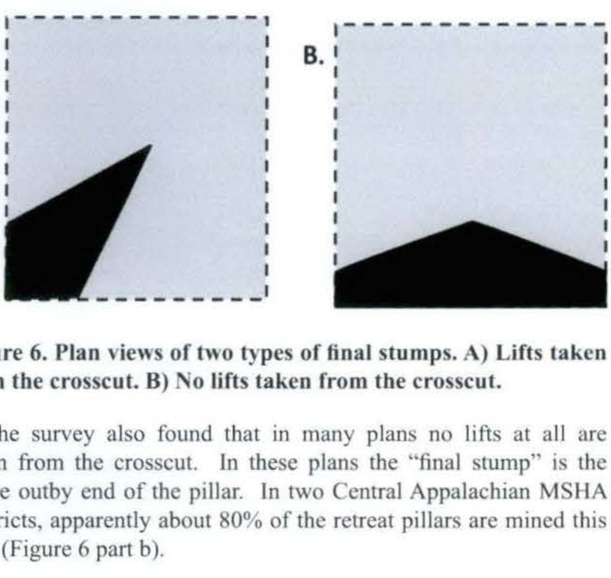

Figure 6. Plan views of two types of final stumps. A) Lifts taken from the crosscut. B) No lifts taken from the crosscut.

The survey also found that in many plans no lifts at all are taken from the crosscut. In these plans the "final stump" is the entire outby end of the pillar. In two Central Appalachian MSHA Districts, apparently about 80% of the retreat pillars are mined this way (Figure 6 part b).

Mobile Roof Supports: Traditionally, timber posts provided supplemental support for pillar recovery. More than 100 roadway, turn, and breaker posts could be required to extract a single pillar (Chase et al., 1997). But setting posts on a pillar line is a very high-risk activity. Between 1998 and 2007, six retreat miners were killed while setting posts. Timber posts also have a number of disadvantages as roof supports, and their weight and bulk can result in material handling injuries.

Figure 7. A mobile roof support.

Mobile Roof Supports (MRS) are shield-type supports mounted on a crawler frame (Figure 7). The advantages of MRS over timber supports are that they:

- Reduce miner exposure to roof falls at the pillar line since they can be operated remotely,
- Provide an active support pressure to the roof at the pillar line,
- Provide larger overall capacity (one 600 ton MRS is approximately equivalent to 12 posts).
- Maintain load through a much greater range of displacement, and
- Decrease the potential for material handling injuries.

For all of these reasons, both MSHA and NIOSH have advocated the use of MRS for pillar recovery since their introduction more than 20 years ago.

Another survey of Roof Control Supervisors in Central Appalachia, conducted in 2015, found that about 60% of the hours worked at retreat mines were at operations that used MRS. This contrasts with the NIOSH (2010) finding that more than 80% of deep cover pillar recovery mines used MRS. The explanation is likely that the deeper retreat mines tend to be in thicker seams. The operating range of MRS is usually limited to seams thicker than approximately 42 inches, and apparently few mines with seams thinner than 52 inches use MRS.

Roof bolts: Roof bolts are the only overhead protection miners have during pillar recovery unless they are under the haulage equipment canopies. Yet in all but one of the fatal retreat mining incidents that occurred between 1996 and 2007 the victims were located beneath bolted roof.

In traditional roof control plans, retreat sections were typically supported by the same roof bolt patterns used elsewhere in the mine. Now we recognize that pillar lines, like longwall headgate and tailgate entries, are subjected to abutment loads and therefore normally require *extra* roof support. Typically the extra support consists of 4-6 cable bolts installed in the intersection in anticipation of the more severe conditions that will be encountered during retreat mining. NIOSH (2010) found that 87% of the retreat mines they studied incorporated such extra roof bolt support, and the authors believe that the percentage is even higher today.

WORK PROCEDURES AND WORKER LOCATION

Successful pillar extraction requires attention to detail. Fatal accidents, some involving multiple fatalities, have occurred when miners were standing unnecessarily close to the pillar line. In other cases poor mining practices have contributed to fatalities. Some of the best practices which have been developed, and which are covered in more detail in the Handbook, are discussed below.

Cut sequence: Federal regulations require that the roof control plan contain drawings that show "the sequence of mining pillars." If a panel configuration differs from the one shown in the plan, such that the sequence in the drawings is no longer applicable, then a panel-specific mining sequence should be developed before the panel is retreated. This is especially important when the panel has a change of direction, a factor which contributed to a double fatality in KY (MSHA, 2005).

Cut dimensions: A 2013 survey of MSHA roof control supervisors found that a large majority of retreat mines limit the pillar lifts to one continuous miner (CM) head width. In essence, the CM is run directly into the pillar to its maximum allowed depth, and then backed straight out. Typically, the attack angle is only about 50 degrees from the entry. One advantage of making such a cut, without turning in the lift, is that it minimizes the time spent in any one cut. Another is that the CM can quickly back out if roof conditions worsen, or it can be pulled straight out if it gets caught by a rock fall.

Where this method is used, the lifts are started just far enough back along the rib to allow the CM head to clear the mobile roof support or posts. Sometimes a thin coal fender is left between cuts at the rib line to assist in roof control. As the lift progresses into the pillar, the CM will typically cut into the previous lift to maintain ventilation.

Unfortunately, the direct attack method only allows the CM to extract 25 feet or so of the pillar. This means that a large coal remnant is left in the middle of the block if the pillars are more than 50 feet wide. Wider pillars are often necessary to support the overburden in thicker seams under greater cover. An alternative to the direct attack is to enter the pillar and then gradually work the CM to a greater angle of penetration into the pillar. In this manner pillars up to about 70 feet wide can be almost entirely recovered.

The practice of starting the new lift 20-25 feet back from previous one, and then widening it out to remove all the coal between the lifts, should be avoided. This technique was in use at a retreat mine in Utah when the roof fell in front of the MRS, killing the CM operator and injuring the helper (MSHA, 2013a). If the cut must be widened in this manner, then a solid coal fender should be left between the lifts to help support the roof.

Worker position: The pillar line is a dangerous place, and miners should never congregate there. No one except haulage equipment operators should be inby the continuous mining machine operator while a pillar is being mined. Only those miners necessary to mine coal and/or install supports should be working or travelling in the work area, including the intersection. Under no circumstances should anyone travel inby installed breaker posts or into a region where pillar recovery has been completed.

The position of the continuous mining operator is another concern. The CM operator normally must handle the miner cable, keeping it against the pillar rib and out of the way of the shuttle cars. He also must stay clear of the CM boom, the haulage cars, and possibly hazardous ribs. For all these reasons, when taking the left-hand cut with a machine cabled on the right, the CM operator is usually located inby the CM, between the CM and the MRS (or turn posts). One disadvantage of this inby location is the potential lack of egress, particularly when the CM is just beginning its cut (Figure 8a). When taking the right-hand cut, the CM operator usually stays close to the right rib, outby the CM. He can handle the cable from here and stay out of the way of the boom and the shuttle cars. He is also outby all previous lifts (Figure 8b).

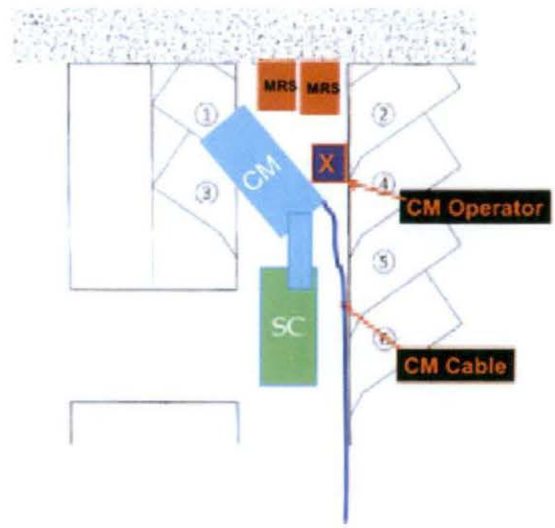

Figure 8a. Position of the continuous miner operator during pillar extraction with a machine cabled on the right-hand side. A) A left-hand cut.

Mobile roof supports: While MRS can be a highly effective means of reducing the risk of pillar recovery, they must be used properly. Fatalities have resulted when workers have been standing too close to them, or did not follow standard operating procedures (MSHA, 2007a; MSHA 2003). After evaluating these fatalities, MSHA released a number of best practices, including:

- Upon completion of mining in a given pillar, the units should be moved sequentially until they are between intact coal pillars.
- At least one unit should be pressurized against the roof at all times.
- Personnel should remain at least 25 ft away from MRS when they are being pressurized or depressurized.

- Plans for performing maintenance in safe locations and for retrieving disabled or immobilized MRS should be formulated in advance and strictly followed.

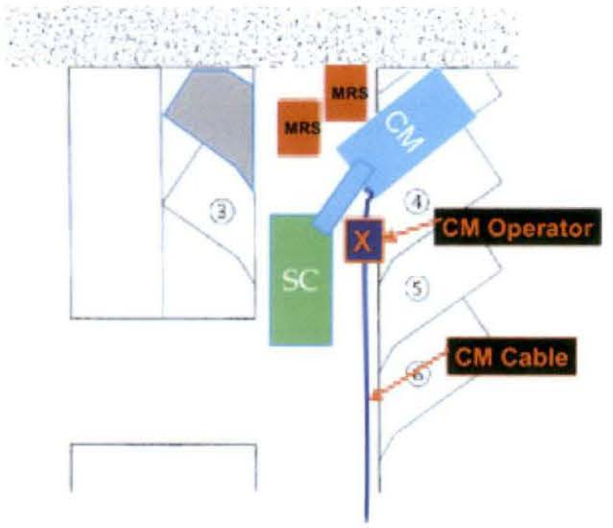

Figure 8b. Position of the continuous miner operator during pillar extraction with a machine cabled on the right-hand side. B) A right-hand cut.

Worker training: Prior to any retreat mining, all persons engaged in retreat mining (including new crew members) should be trained in the provisions of the approved roof control plan relative to retreat mining. Training shall be conducted before retreating of a new panel begins.

Stability assessments: Retreat mining imposes additional stresses and strains on a mine roof. Rock that seemed stable after development can suddenly be broken or pulled apart. Weak rock, or rock that contains pre-existing geologic fractures, is particularly susceptible.

Conducting a geologic assessment of the entire panel before retreat mining commences is an important best practice. The assessment should identify major roof fractures, which can then be marked, mapped, and supported. Some mines use paint or flags to note the presence of faults, hillseams (open joints), or other hazardous features. It is good practice to plan to skip some lifts in order to leave coal as support for such features. Appendix H of the MSHA Handbook contains further suggestions on conducting a pre-retreat mining hazard assessment.

In the past, poor conditions were often observed in the area before the retreat mining fatality occurred, but no action was taken (Mark and Zelanko, 2005). Ideally, pre-shift and on-shift examinations should include a thorough assessment of geologic conditions, and hazards should be reported and dangered off or appropriately supported. Examinations that include areas outby the pillar line can be used to anticipate geologic conditions prior to retreat.

Test holes are useful to determine if there is roof separation, and they can be monitored during mining to see if conditions worsen. The pressures and loading rates visible on MRS gauges also provide information on roof stability. Mine-specific "trigger points" indicating anomalously high loads or loading rates can be identified, along with the procedures that should be employed to respond to them.

RIB FALLS AND COAL BURSTS

As roof fall accidents have become less frequent, bursts and rib falls have become more prominent. Hazardous roof falls can occur during pillar extraction regardless of the depth of the mining. Rib falls and coal bursts, on the other hand, are much more likely to occur under deep cover.

Rib falls are a serious hazard at deep cover pillar recovery mines. During the period 2010-2015, eight miners were killed by rib falls in room-and-pillar operations. Only one of those rib fatalities occurred on a pillar line, but another five were at mines that sometimes employed pillar extraction. The most recent rib fall fatality occurred in January of 2016 during development mining at the only active pillar retreat mine in PA.

The two main factors that lead to an increased risk of rib falls are thicker coal seams and higher stress levels (Gauna and Mark, 2011). For example, analysis of the eight recent fatal room-and-pillar rib fall incidents reveals that:

- Seven occurred where the depth exceeded 700 feet and/or a multiple seam interaction was present, and
- The mining height exceeded seven feet in all but one case.

Rib bolting can be highly effective in reducing the risk of rib falls. Rib bolts should be installed using inside-control roof bolting machines, where the drill heads are between the operators and the ribs.

Coal bursts are defined as the sudden, violent ejection of coal or rock into the mine opening. Despite decades of research, the sources and mechanics of bursts are imperfectly understood, and the means to predict and control them remain elusive.

Coal bursts have long been among the most feared hazards in deep retreat mines. Eighty years ago Rice (1935) described bursts in the coal mines of Harlan County, KY, and Wise County, VA. A comprehensive database of 172 burst events that occurred between 1936 and 1993 indicated that more than 80% of the bursts reported by room-and-pillar mines occurred during the process of pillar or barrier pillar recovery (Iannacchione and Zelanko, 1995).

The incidence of non-longwall bursts in room-and-pillar mines has decreased significantly with time. Figure 9 shows that during the 1980s and 1990's, there were about six bursts per year in locations other than the longwall face. The rate has fallen to less than 2 per year since then. There have been just six non-longwall bursts since 2010.

Unfortunately, three of those six bursts resulted in fatalities or permanently disabling injuries. All three were during pillar recovery, two in KY and the third in WV. None of these mines had ever reported a burst before.

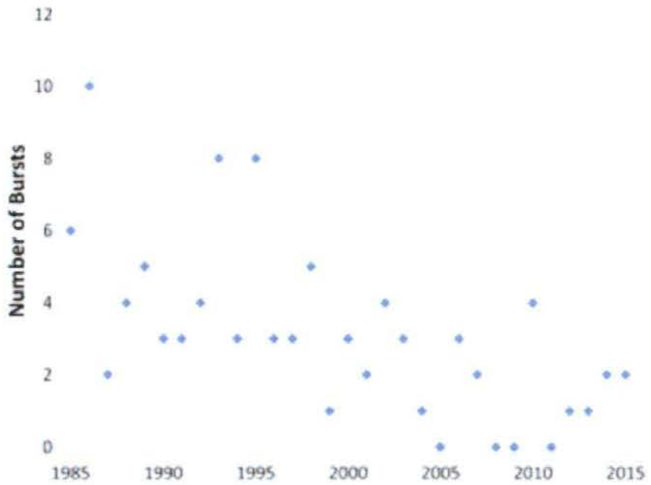

Figure 9. Bursts in US coal mines (excluding the longwall face), 1984-2015.

Pillar design is the primary engineering control for minimizing the risk of pillar failures and coal bursts during retreat mining under deep cover. In the past, many large bursts have occurred where the barrier pillars were too small, were being extracted on retreat, or were not used at all. In some of these cases, pillar splitting operations without a barrier pillar apparently triggered the burst (NIOSH, 2010).

Inadequate pillar design did not seem to play a role in any of the recent coal bursts, however. In one KY case, the MSHA investigation concluded that a multiple seam interaction, stronger roof geology, and an improper pillar extraction sequence contributed to the fatal burst (MSHA, 2013b). Multiple seam interactions and geological conditions contributed to the WV burst as well (MSHA, 2014). Other large bursts have occurred during development mining at deep cover room and pillar mines, fortunately without injuries (Newman, 2002; Gauna and Phillipson, 2008).

Risk management programs for the coal burst hazard in room and pillar mines have been presented (Mark and Gauna (2015); Zhang et al. (2015)). Underground observations and monitoring are critical elements of such programs. Mining crews should be trained to observe coal burst warning signs, particularly the occurrence of small bursts, which are often the best indication that an area is becoming more burst prone. A record-keeping system should be maintained and management processes developed to ensure that warning signs receive appropriate responses. Both of the recent fatal coal bursts during pillar recovery were preceded by smaller bursts whose implications were not heeded.

CONCLUSIONS

Long considered "inherently" dangerous, the past eight years have shown that pillar recovery can be conducted as safely as other types of underground mining. The rate of fatal roof falls, based on exposure hours, has apparently been reduced by a factor of more than ten. This success was achieved through the widespread application of better ground control practices identified through a rigorous evaluation of past failures. The new paradigm is also based on an updated understanding of the basic rock mechanics of pillar recovery. It is built around the concepts of *global* and *local* stability, and replaces the traditional emphasis on "complete extraction." The third essential component of the new approach is an emphasis on the management of work procedures during pillar recovery operations.

Remaining challenges include rib failures and coal bursts. Both hazards are most severe in the mines under deeper cover.

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