RESEARCH REPORT ON THE COAL PILLAR RECOVERY UNDER DEEP COVER

Office of Mine Safety and Health Research
National Institute for Occupational Safety and Health
Centers for Disease Control and Prevention
Department of Health and Human Services

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EXECUTIVE SUMMARY

Background

Retreat mining has always been an integral part of underground coal mining.[1] When room-and-pillar methods are employed, large blocks of coal in the form of pillars are initially left in place to support the great weight of the overburden (cover). Unless these pillars are subsequently extracted, the coal they contain can never be recovered. Pillar recovery in underground coal mines is an important consideration for maximizing resource recovery since any coal left in place that isn't recovered is lost. This is a consideration for the mining operation and the leaseholder of the coal property since maximum recovery needs to be considered in the mine plans. Coal mining on public lands requires the operator to obtain approval for the mine plan from the U. S. Department of Interior's Bureau of Land Management (BLM) which is the federal agency that has responsibility for verifying that the operator was achieving maximum economic recovery of coal under a federal lease.[2]

Historically, retreat mining has been less safe than other underground mining techniques. Pillar recovery removes the overburden support, allowing the overlying rock to cave and subside. This intentional caving is an unavoidable part of the retreat mining process, but if it occurs prematurely it can cause roof falls that put miners at risk. A National Institute for Occupational Safety and Health (NIOSH) study published in 2003 found that retreat mining elevated a miner's risk of being killed in a roof fall by a factor of three.

However, retreat mining's safety record has substantially improved recently. Many mines have implemented safety measures and best practices advocated by NIOSH, the Mine Safety and

[1] In this report, the term "retreat mining" will refer exclusively to room-and-pillar retreat mining, and will not include longwall mining. Longwall mines are generally much larger than room-and-pillar mines, employing about 400 people in each longwall mine compared to only about 70 at a typical room-and-pillar mine.The terms "retreat mining" and "pillar recovery" will also be used interchangeably.

[2] Independent Review of MSHA's Actions at Crandall Canyon Mine Genwal Resources, Incorporated, Huntington, Emery County, Utah, United States Department of Labor.
http://www.msha.gov/CCreview/CrandallCanyonIndependentReview.pdf.

Health Administration (MSHA), and state regulatory agencies. An increased amount of roof support is being installed to protect miners from roof falls due to premature caving. During the past 4 years, there has been one fatal roof fall during retreat mining, compared to an average of two per year during the previous decade.

However, roof falls are just one of the hazards that retreat miners face. On August 6, 2007, six miners were killed in a widespread pillar failure that resulted in violent coal bursts[3] and a massive mine collapse. Three would-be rescuers were killed in a second event 10 days later. The MSHA report on the Crandall Canyon Mine incident cited the cause of the disaster as a flawed mine design, whereby the stress level encountered "exceeded the strength of a pillar or group of pillars near the pillar line."[4] The report documented how the two pillar design software packages used to develop the mine plan, the Analysis of Retreat Mining Pillar Stability (ARMPS) and LaModel, had been employed improperly. With cover that exceeded 2,200 ft at its deepest point, the retreat mining at Crandall Canyon was some of the deepest ever attempted in the U.S.

Purpose

In the FY 2008 Appropriation (Public Law 110-161), Congress directed NIOSH to:

> "conduct, in collaboration with the University of Utah (U of Utah) and West Virginia University (WVU), a study of the recovery of coal pillars through retreat room-and-pillar mining practices in underground coal mines at depths greater than 1,500 ft. The study should examine the safety implications of retreat room-and-pillar mining practices, with emphasis on the impact of full or partial pillar extraction mining. The study should include, but not be limited to, analyses of:
>
> (1) The conditions under which retreat mining is used, including conditions relating to seam thickness; depth of cover; strength of the mine roof, pillars, and floor; and the susceptibility of the mine to seismic activity;
> (2) The procedures used to ensure miner safety during retreat mining.
>
> The report shall include recommendations to enhance the safety of miners working in underground coal mines where retreat mining in room-and-pillar operations is utilized. Among other things, the recommendations should identify means of adapting any practical technology to the mining environment to improve miner protections during mining at depths greater than 1,500 ft, and research needed to develop improved technology to improve miner protections during mining at such depths."

[3] The terms "burst," "bump," and "bounce" are often used interchangeably in the mining literature. In keeping with its usage in the Code of Federal Regulations (CFR), Part 50-2-2h, this report will use the term "burst."
[4] Fatal Underground Coal Burst Accidents, August 6 and 16, 2007. Report of Investigation. United States Department of Labor, Mine Safety and Health Administration.
http://www.msha.gov/Fatals/2007/CrandallCanyon/CrandallCanyonreport.asp

NIOSH was directed to submit a report, not later than 2 years after beginning the study, containing the results of the study to the Committees on Appropriations of the House of Representatives and the Senate.

In preparing this report, NIOSH actions were as follows: (1) in consultation with the Mine Safety and Health Research Advisory Committee (MSHRAC)[5] on January 22-23, 2008, the scope of work was defined and the research endorsed approved; (2) on February 13, 2008, meetings were held at the Pittsburgh Research Laboratory with professors from West Virginia University and the University of Utah to discuss the research tasks, after which preparation of statements of work were initiated for each university; (3) in March, 2008, the first of 30 mine visits was conducted by NIOSH researchers to study pillar design and retreat mining plans at those mines; (4) based on the MSHRAC scope of work, contracts were awarded on April 4, 2008, to West Virginia University, and on June 5, 2008, to the University of Utah. These contracts were followed by drafts of reports from the universities in 2009; and (5) in April, 2009, the final of 30 mine visits was conducted by NIOSH researchers.

Approach to the Study on Coal Pillar Recovery

The focus of this study was the safety of miners in room-and-pillar retreat mines that have recent experience recovering pillars at depths in excess of 1,500 ft.[6] The most significant hazards faced by these miners are:

- Ground falls resulting in injuries or fatalities. Ground falls include large “roof falls” that involve failure of the roof support, smaller “rock falls” that occur between roof supports, and “rib falls” that come from the side walls of the mine.
- Pillar failures that can affect large areas of a mine, but are usually non-violent “squeezes” that occur slowly and seldom result in injuries to mine workers.
- Coal bursts, which are violent seismic events that cause coal to be ejected into the mine with enough energy to injure or kill miners.

NIOSH determined that the risks that miners face in the deepest operations are not limited to only those depths, and therefore NIOSH broadened the study to involve a number of retreat mines with working depths between 1,000 and 1,500 ft.[7] NIOSH also evaluated ground control safety procedures and technologies used by shallow cover retreat mines, longwall mines, and even non-coal mines, both in the U.S. and globally, that could potentially improve miner protections during deep cover retreat mining.

The study built upon extensive past NIOSH retreat mining research (Mark and Tuchman, 1997; Chase et al., 2002; Mark and Zelanko, 2005). To conduct the current study, 14 different coal companies cooperated with NIOSH by sharing information on the industry’s experience with deep cover pillar recovery. NIOSH researchers visited 30 deep cover retreat mines located in

[5] The MSHRAC advises NIOSH on the conducting of mine safety research. The Committee consists of 10 members appointed by the Secretary, Health and Human Services, and it includes a broad range of experts as well as representatives from MSHA, the mining industry, and labor.

[6] Mines practicing both full and partial pillar recovery were included in the study, although most retreat mining plans fall somewhere between full and partial recovery.

[7] In this report, “deep cover” will refer to depths greater than 1,000 ft, while “deepest cover” will be reserved for depths greater than 1,500 ft.

Utah, Colorado, West Virginia, Virginia, and Kentucky. Information on past mining experience and pillar recovery practices was gathered from all these mines, and underground investigations were conducted at 18 of them. The mines that were visited included nearly every active U.S. mine that has recovered pillars at depths exceeding 1,500 ft, and the majority of mines with experience between 1,000 and 1,500 ft. By combining the information collected from the mines with data obtained from MSHA roof control specialists and the MSHA accident and injury database, NIOSH obtained a detailed and current picture of the deep cover retreat mining segment of the industry.

The field studies that NIOSH conducted at the deep cover retreat mines also provided more than 200 new retreat mining case histories for the ARMPS database. ARMPS is the NIOSH-developed software currently being used by the mining industry to size pillars for retreat mining. ARMPS is already a critical mine safety technology, and since it is an empirical model, expanding the case history database enhances the pillar design guidelines.

The NIOSH study focused particularly on coal burst control and prevention, because the burst hazard is most severe in deep cover mines. NIOSH compiled a comprehensive 25-year database of bursts in retreat mines, and conducted in-depth analyses of the most hazardous multi-pillar burst events. In addition, NIOSH facilitated Major Hazard Risk Assessments (MHRA) of deep cover pillar recovery operations at two cooperating coal mines.

Under contract with NIOSH, studies were also conducted by the U of Utah and WVU. A WVU team investigated pillar design for deep cover retreat mining, focusing on the LaModel numerical modeling program. The U of Utah effort concentrated on the use of seismic monitoring to help reduce the risk of coal bursts.

Evaluation of the Conditions under Which Retreat Mining is Used

Approximately 39,000 U.S. miners work in underground coal mines, and about 25% of them work at mines that recover pillars. Since only about one-third of the coal produced at these mines comes from the extraction of pillars, the total exposure to pillar recovery is less than 10% of all hours worked underground. About 90% of all room-and-pillar retreat mining production is located in the Central Appalachian coalfields of southern West Virginia, eastern Kentucky, and western Virginia, with only 2% coming from Colorado and Utah.

There are 14 U.S. mines that have recently recovered pillars at depths greater than 1,500 ft, and these mines employ fewer than 1,000 miners. All of these mines, except one in Utah, are located in Harlan County, KY, or the neighboring counties of Wise in Virginia and Perry in Kentucky. In all, NIOSH estimates that less than 0.5% of all underground hours worked in coal mines are involved with recovering pillars at depths greater than 1,500 ft. About 27 mines recovering pillars at depths between 1,000 and 1,500 ft are located throughout central Appalachia, and one more is located in Colorado. These mines employ approximately 2,200 miners. At these mines, there has been almost no pillar recovery at depths in excess of 2,000 ft during the past 10 years.

The seam thickness at 87% of the mines NIOSH visited during the current study was between 5 and 8 ft. One mine is working a seam that is less than 5 ft thick, and three others were extracting “twin seams” with a total height in excess of 10 ft.

In general, the roof and floor rocks in the Colorado, Utah and Central Appalachian coalfields are significantly stronger than those found in other U.S. coalfields, and the deep cover mines conform to this trend. Coal seam strength, on the other hand, is very difficult to measure, but does not seem to vary significantly from region to region. Regardless of coal seam strength, empirical evidence and laboratory testing suggest that almost any bituminous coal[8] can burst.

About 80% of deep cover retreat mines are located above or beneath previously mined seams. Multiple seam interactions can increase the likelihood of ground falls, pillar squeezes, and bursts.

Seismicity is an inevitable part of the mining process, particularly when caving occurs and the overburden fractures and subsides. Coal bursts, which are violent seismic events that occur in the coal seam, are relatively rare, however. Even a large seismic event in the overburden may not be associated with a violent coal burst underground.

A comprehensive burst database, developed by NIOSH from MSHA statistics and other sources, shows that in recent times, bursts have been rare events in room-and-pillar mines. Other than the ones at Crandall Canyon, there has been just one fatal coal burst during pillar recovery since the mid 1980s. Only two of the room-and-pillar mines in operation today have ever reported a burst.

While the majority of the reported bursts during the past 25 years have been relatively small, there were 17 bursts that affected multiple pillars simultaneously. Crandall Canyon was, by far, the largest of these multi-pillar bursts, but three others (in 1983, 1984, and 1996) resulted in fatalities.

The incidence of bursts appears to increase significantly as the depth of cover increases. Burst-prone areas of mines are also usually characterized by very strong roof and floor. A few multi-pillar bursts have occurred in room-and-pillar mines where no retreat mining was being conducted. These have been associated with multiple seam mining and nearby faulting.

Evaluation of Procedures and Technologies Used to Ensure Miner Safety

Safety professionals utilize a range of interventions or tools, including engineering, administrative, and personal protective equipment, to eliminate or mitigate hazards. In the course of this study, NIOSH evaluated a wide range of procedures and technologies that are used to protect miners from the hazards of retreat mining. Engineering procedures encompass all aspects of mine planning, including layout, pillar design, support selection, and selection of mining sequence. They can reduce or eliminate risks before miners are ever exposed to them, and as such are generally the surest way to improve retreat mining safety. Administrative procedures, such as workplace observations (e.g. looking for signs of instability), can contribute to an improvement in retreat mining safety, especially if combined with appropriate Training Interventions. Training would include, for example, a review of the hazards associated with, operational practices to reduce risk, and specific actions to be taken during retreat mining.

[8] Nearly all the coal that is mined underground in the U.S. today is of bituminous rank. A very small amount of anthracite coal is mined in eastern Pennsylvania.

Administrative procedures and training interventions are generally less effective than engineering procedures, because the retreat mining process requires that miners be located 20-40 ft from where the coal is being cut, even when equipment is operated by remote control.

Personal Protective Equipment is not a practical option because the retreat mining process requires that miners be located in close proximity to potentially large roof falls or coal bursts in which a person wearable device would be ineffective.

Statutory interventions, e.g. using a regulation to enforce a specific practice, are common in mining and other industries. The most important statutory procedures for retreat mining are included in Part 75, Title 30 of the Code of Federal Regulations (30 CFR 75). The regulations that specifically address retreat mining[9] have not been updated in several decades, and therefore they do not cover many of the new procedures and technologies that are discussed in the following sections of this report. MSHA also uses policy to clarify statutory interventions. For example, the Program Information Bulletins (PIBs) and other documents that describe 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). While regulations are an essential component of retreat mining safety, they alone will not prevent harm to mineworkers. A major hazard risk assessment and management plan is an important augmentation, and such a plan would include engineering, administrative, and training interventions in a complementary fashion (Iannacchione, Varley, and Brady, 2008).

Technology continues to play an important role to improve safety and health in the mines. Roof supports, including rock bolts, cable bolts, and Mobile Roof Supports, are the technologies that are most important in the prevention of ground falls. No support system can protect workers from violent coal bursts, however. Some stability monitoring and warning devices have been proposed over the years (for example, see Maleki and McVey, 1988), but none have ever proved to be effective. Seismic and microseismic monitoring has made great strides in the past 3 decades, but at best, this monitoring provides useful insights into rock mass behavior and mine design performance rather than providing warning of an imminent failure. Retreat mining is conducted in such a wide range of geologic conditions, and those conditions can change so rapidly, that it would be unreasonable to expect any single technology to provide reliable protection in all circumstances.

At this time, no major new technological solutions are envisioned to mitigate the hazards associated with retreat mining. Instead, as will be presented in this report, the application of multiple interventions combined with new criteria for pillar extraction will reduce the risk of injury to mineworkers who are engaged in retreat operations.

Protection from Roof, Rock, and Rib Falls

Retreat mining has historically been associated with a disproportionately high rate of roof fall fatalities, but in recent years the record has improved significantly. This improvement can be

[9] The two most relevant of these are Section 75.207, "Pillar Recovery, and Section 75.222.d, "Roof Control Plan Approval-Criteria."

directly linked to the widespread adoption of best practices and design techniques, particularly three key safety technologies:

(1) The practice of leaving engineered final stumps[10] in place rather than extracting the entire pillar;
(2) The use of extra roof bolts for added support, particularly in the intersections;
(3) The use of Mobile Roof Supports to replace manually set timber posts.

Analysis of the MSHA-approved Roof Control Plans that NIOSH obtained from the deep cover retreat mines shows that these operations have a high rate of adoption (in excess of 80%) of all three key safety technologies. Retreat mines are also using a variety of other safety measures related to mining method, cut sequence, and support installation in order to minimize the risk of roof falls.

MSHA statistics indicate that, on average, deep cover pillar retreat miners are injured by small falls of rock at about the same rate as other room-and-pillar miners. Many of these injuries could be prevented if more mines used roof screen to prevent rock falls.

Deep cover retreat miners are about three times more likely to be injured by rib falls than other room-and-pillar miners. The deep cover mines that have the lowest rib fall injury rates install rib bolts, and they employ inside-control roof bolting machines that protect the operators from rib falls.

In recent years, the technique of Major Hazard Risk Assessment has been proposed as a method for identifying and reducing the hazards of underground mining. As part of this study, NIOSH facilitated trials of MHRA techniques at two deep cover retreat mines, involving teams of experienced mine employees. The MHRA process demonstrated its potential to help mining operations lessen the risk of deep cover pillar recovery, but only if they follow through by implementing, monitoring, and auditing the control measures that are identified.

Preventing Pillar Failures

Proper pillar design is essential to maintain the stability of underground mine workings. Today, nearly all retreat mines use the NIOSH ARMPS software to size their pillars, including the barrier pillars that isolate each active panel from panels that have been previously mined out.[11] Most retreat mines also employ the NIOSH AMSS (Analysis of Multiple Seam Stability) software as appropriate. Some mines employ other engineering techniques or rely on local experience, in conjunction with ARMPS, for pillar design. The LaModel software is also employed by some mines and ground control consultants, primarily for complex mining geometries that are difficult to analyze with ARMPS.

After the Crandall Canyon disaster, MSHA released a series of memos and other documents which define the pillar design best practices (such as using ARMPS) that mine operators should

[10] The "final stump" is the last remaining part of the coal pillar after the rest of the pillar has been extracted.
[11] *Barrier pillars* are large, unmined blocks of coal that are left in place to isolate active workings from previously mined-out areas. In retreat mining applications, properly designed barrier pillars protect mine workings from the high stresses that occur next to caved areas that were previously mined out.

follow when preparing their Roof Control Plans.[12] The widespread implementation of these best practices has greatly reduced the risk of pillar failures that affect large areas of the mine.

As part of this study, NIOSH re-evaluated the ARMPS program using the expanded case history database. Statistical analysis confirmed that the current ARMPS program and guidelines are effective in greatly reducing the risk of pillar failure. Empirical analysis, combined with numerical modeling, also suggested that, under deep cover, barrier pillars may be carrying more load than had been previously thought. A "pressure arch" loading algorithm that reflects the additional load applied to the barrier pillars was developed and implemented in a new version of ARMPS along with several other minor improvements. Analysis shows that the new ARMPS meets or exceeds the level of protection provided by the current ARMPS program.

Under NIOSH contract, WVU focused on improvements to the LaModel program. Using case histories from the ARMPS database, the researchers developed standardized best practice procedures for calibrating critical LaModel input parameters for site-specific conditions. They also developed criteria that can be used to evaluate prospective designs and compare them to ones in the database. These improvements, as well as several that improve LaModel's operating performance and user friendliness, are being implemented into a new version of the program.

One of the lessons of the Crandall Canyon disaster was that mine planners need to understand both the theory and practice of ground control. The U.S. lags behind other coal mining countries in its employment of engineers with expertise in ground control and other mining specialties. Such expertise is essential to design and operate safe mines in the uncertain underground environment, particularly at great depth. NIOSH will advance industry understanding of both theory and practice by conducting a major pillar design training initiative during 2010, focused on the enhanced versions of ARMPS and LaModel that are being developed. In the longer term, however, NIOSH believes that improvement will require a cultural shift in which the universities produce, and the mining companies employ, more specialists that can apply their expertise to reduce risk and improve mine safety.

Burst Control

Burst control procedures and technologies include geologic assessment, mine design, operational practices, and monitoring. One assessment technique that has been used in deep cover retreat mines is to identify regions, called "red zones," that are considered to be burst-prone. The "red zones" are defined by a combination of the depth and geologic factors that have been associated with past bursts. Within the red zones, mining should be limited to minimize the risk of bursts.

Proper mine layout, particularly limiting the panel width and using barrier pillars, is believed to be the best defense against pillar bursts. ARMPS analysis of the 17 multi-pillar burst case histories indicates that at least 12 of them (including Crandall Canyon and the others involving fatalities) could be attributed to inadequate pillar design. All 12 of these incidents occurred

[12] Precautions for the Use of the Analysis of Retreat Mining Pillar Stability (ARMPS) Computer Program. Program Information Bulletin No. P08-08. United States Department of Labor Mine Safety and Health Administration. http://www.msha.gov/regs/complian/PIB/2008/pib08-08.asp; Procedure Instruction Letter No. I08-V-2. United States Department of Labor Mine Safety and Health Administration. http://www.msha.gov/regs/complian/PILS/2008/PIL08-V-2.asp.

during retreat mining, and in nine of them the analysis showed that the barrier pillars were inadequate to effectively isolate the active panel from overburden loads transferred from previously mined panels. NIOSH research also found that at least four of the 17 events were associated with multi-seam interactions or faulting, and might not have been prevented by better pillar design. Analysis of historical burst events in room-and-pillar mines suggests that the practice of pillar splitting, which requires mining into the highly stressed pillar core, has been associated with a disproportionate number of incidents.

A variety of monitoring techniques, including in-mine observations, probe drilling, seismic tomography, and seismic monitoring, have been employed in burst prone mines in the U.S. and internationally, but none has yet been able to provide reliable advance warning of the time and place of a specific imminent burst. Seismic monitoring is considered to be an essential part of the rock burst control strategies employed by deep metal mines in South Africa, Canada, Australia, and elsewhere. It is also employed in some deep European longwall coal mines. Its value lies in determining relative probabilistic hazard ratings for different mine areas. Currently, regional-scale monitoring of mining-induced seismicity using surface geophones is conducted in Utah and western Colorado. In the Central Appalachian coalfields, surface seismic monitoring stations are so sparse that only the very largest events are recorded.

To evaluate the potential applicability of seismic monitoring to U.S. coal mines, the University of Utah convened a panel of international experts. The panel confirmed that even the most sophisticated seismic monitoring systems in use anywhere in the world cannot *predict* a specific hazardous seismic event in advance. However, the consensus of the expert panel was that seismic monitoring has the potential to improve safety in underground coal mines in two primary ways:

- Allowing improvements of a mine's design by increasing understanding of the causes of seismicity in that mine;
- Providing a means of long- to medium-term seismic hazard assessment.

However, effective seismic monitoring is not easy to implement. It involves complex equipment and interpretation techniques requiring the specialized expertise of a ground control professional.

Recommendations to Enhance the Safety of Retreat Mining

NIOSH recommends that deep cover room-and-pillar retreat coal mines conduct regular burst hazard assessments for any areas where retreat mining is proposed and the depth of cover exceeds 1,000 ft. The assessments will identify "red zones" of significantly elevated burst likelihood based on the depth of cover, the geological conditions, the potential for multiple seam interactions, and recent ground control experience. The assessments should be conducted at least annually, and should be guided by an experienced ground control professional.

NIOSH found that, within an identified "red zone," no combination of currently available mining sequences, administrative procedures, or monitoring techniques can be relied upon to reduce the risk posed by coal bursts to an acceptable level. Therefore, NIOSH recommends that retreat mining should not be conducted within identified "red zones" of significantly elevated burst likelihood. Additional specific recommendations to limit the risk of violent coal bursts during retreat mining operations are:

- At depths exceeding 1,000 ft, retreat mining should not be conducted without properly designed barrier pillars.
- At depths exceeding 1,000 ft, pillar splitting should not be conducted on the pillar line.
- At depths exceeding 2,000 ft, pillar recovery should not be conducted.

Proper pillar design is the most effective technique for minimizing the risk of coal bursts in deep cover retreat mines. To ensure that the mining community has access to the best available pillar design technology, NIOSH will make enhanced versions of ARMPS and LaModel available, together with supporting information and training materials. NIOSH will conduct a training initiative in pillar design, aimed at both industry and regulatory personnel.

To improve the safety during retreat mining, a NIOSH Pillar Recovery Partnership, consisting of representatives from NIOSH, MSHA, state regulatory agencies, coal operators, and labor, is proposed to evaluate the state of the art in pillar recovery. The partnership will address best practices for cut sequences, roof support, special conditions, operator training, and other issues. The ultimate goal of the Partnership will be to develop a handbook that mine operators can use to prepare MSHA-Approved Roof Control Plans for retreat mining.

Research Recommendations

Research should be conducted to develop enhanced guidelines for defining burst-prone "red zones" based on geologic and stress criteria. Guidelines should be developed to provide a more specific definition of a coal burst, and criteria for when coal bursts should be reported to MSHA.

NIOSH also recommends that:

- Research should be conducted to reduce the number of injuries and fatalities associated with rib falls, addressing when and where rib support should be installed, and the proper use of roof bolting machines where the risk of rib falls is elevated.
- Research should be conducted to tailor Major Hazard Risk Assessment (MHRA) techniques to the specific needs of retreat coal mines, and to transfer the technology to these mines. The effort should focus on helping mines follow through with the monitoring and audits that are necessary to the success of the MHRA technique.
- Basic research should be conducted into pressure arch behavior and the mechanics of squat coal pillars.
- Further seismic monitoring research should be conducted at demonstration sites where the technology and interpretation techniques can be tested and refined to advance the state of practice of seismic monitoring for hazard assessment in deep underground coal mines.

Finally, NIOSH believes that mine safety would benefit if more ground control specialists were engaged in mine planning and operations. The mining community should take steps to develop a cadre of specialists with the appropriate practical training and ensure that these specialists are appropriately employed in the industry.

RESEARCH REPORT ON THE COAL PILLAR RECOVERY UNDER DEEP COVER

Background

Retreat mining, or pillar extraction, has always been an important part of room-and-pillar, underground coal mining.[13] A survey published in 2003 found that retreat mining was practiced in nearly 400 underground mines in the U.S. (Mark et al., 2003). Together these mines accounted for 29% percent of the country's underground coal production.

When a new area of a coal mine is developed, a checkerboard pattern of tunnels ("entries") is driven in the coal (figure 1a). Typically, about 50% of the coal is extracted during this development phase. The remaining coal is in the pillars that are left between the tunnels. These pillars serve the critical function of supporting the great weight of the overburden (cover) from the mine level to the surface.

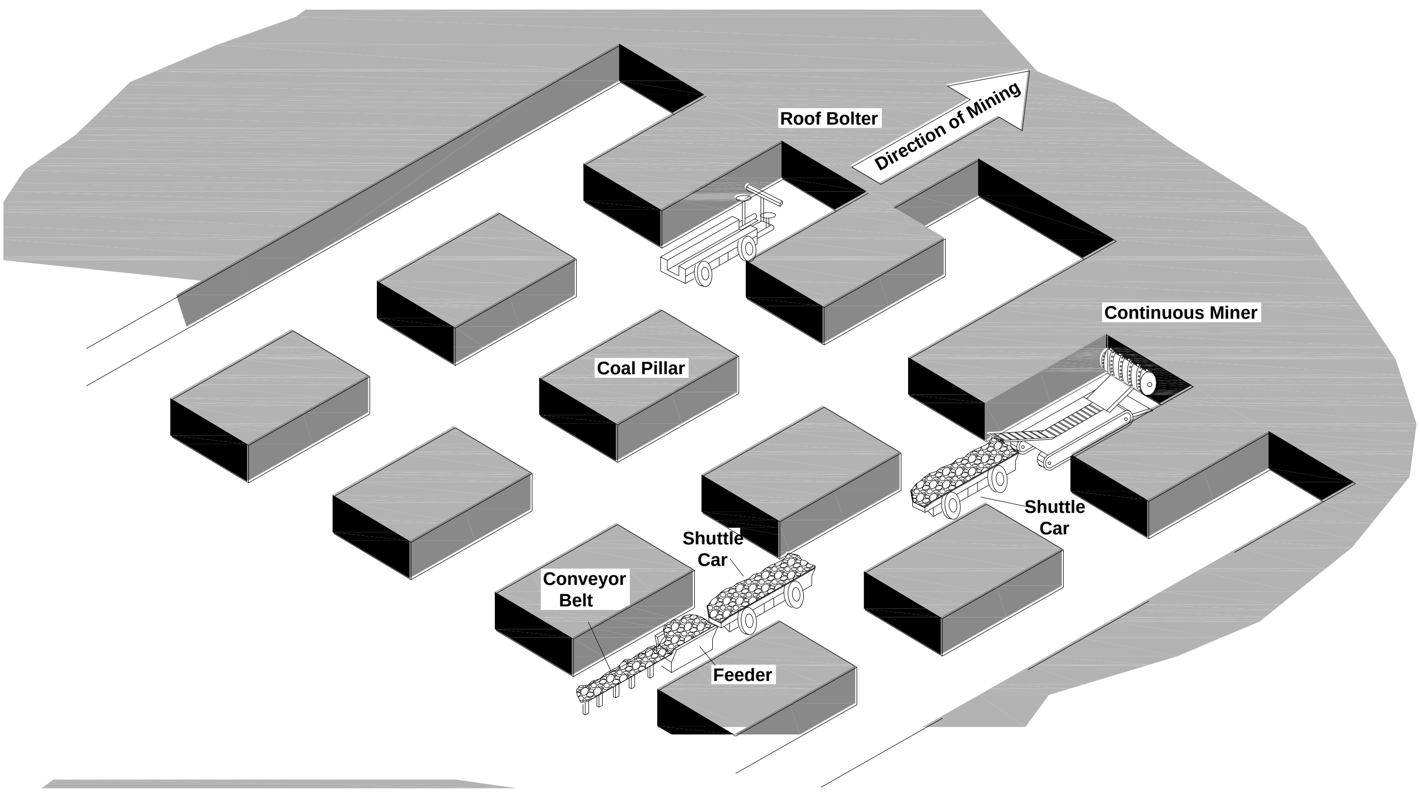

Figure 1a. Development phase of room-and-pillar mining.

Once an area has been fully developed, retreat mining may be conducted to recover the coal that was left in the pillars (figure 1b). The study previously cited estimates that pillar extraction accounts for about one-third of the total production at a typical retreat mine.

[13] Two underground mining methods, room-and-pillar and longwall, are employed in the U.S. today. Each accounts for about half of the underground production. However, while longwall mines extract most of their coal using the longwall technique, they still use room-and-pillar techniques to gain access to the coal, and they occasionally recover some of the pillars they previously developed.

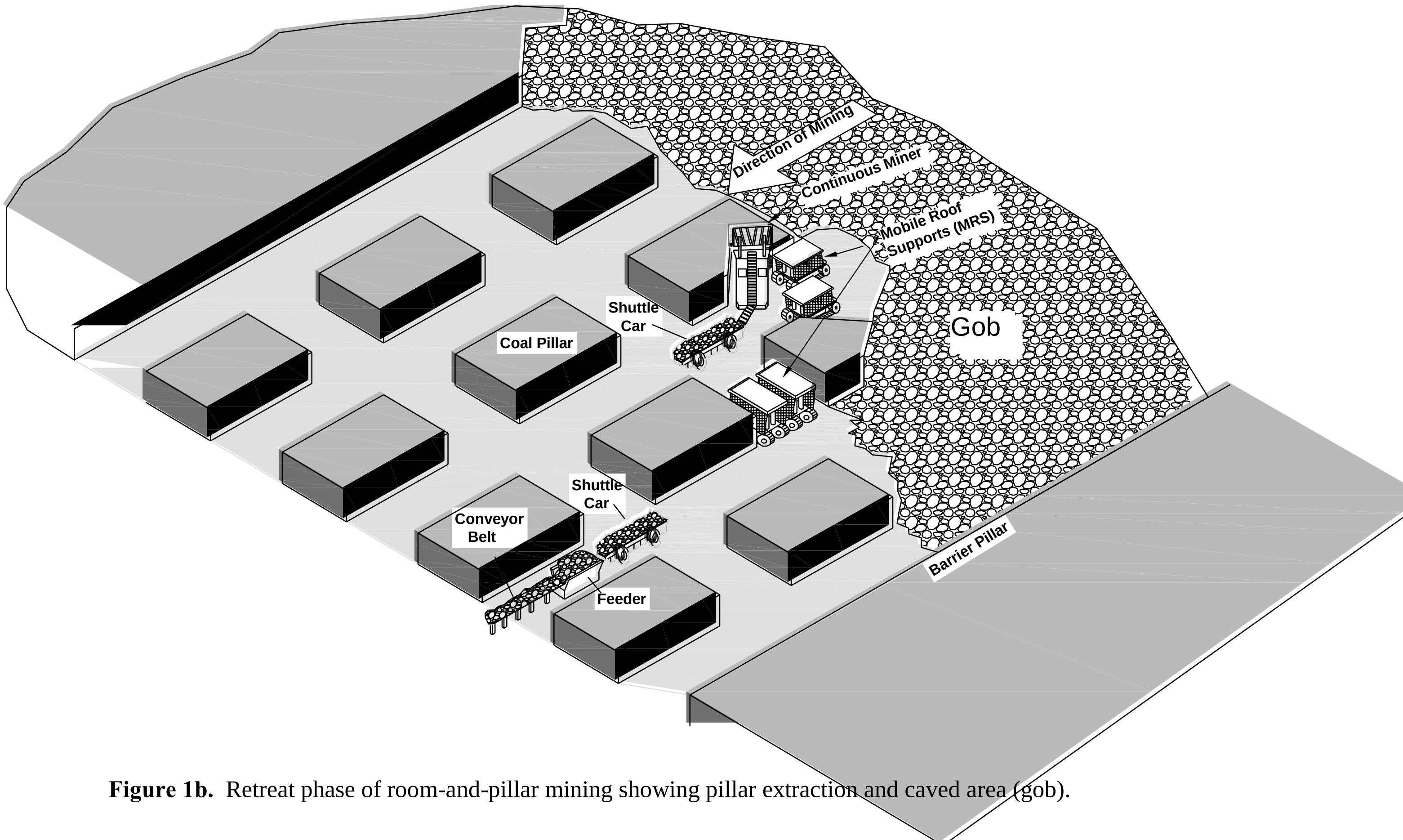

Figure 1b. Retreat phase of room-and-pillar mining showing pillar extraction and caved area (gob).

As the pillars are being removed, the roof above the worked-out area caves and the overburden subsides. Because premature caving can cause hazardous roof falls while the miners are still present, retreat mining has historically been less safe than other underground mining methods. Previous studies found that between 1989 and 2001, 25% of all ground fall fatalities in underground coal mines occurred during retreat mining (Mark et al., 1997; Mark et al., 2003). These same studies estimated that retreat mining accounted for less than 10% of all hours worked underground. Therefore, during this period a miner on a retreat section was three times more likely to be killed in a ground fall than a miner engaged in another activity underground.

In recent years, the safety record of retreat mining has improved significantly. Figure 2 shows that prior to 2005, each year saw an average of two fatal roof falls during pillar recovery operations. Since August 2005, however, there has been just one fatal roof fall during pillar recovery operations. The improvement is likely due to concerted efforts made by the National Institute for Occupational Safety and Health (NIOSH), the Mine Safety and Health Administration (MSHA), state regulatory agencies, and coal companies to develop and implement safer retreat mining technology and procedures. These efforts will be discussed in later sections of this report.

Unfortunately, roof falls are not the only hazards faced by miners engaged in pillar recovery. The high stresses that are created by the caving process can also cause pillar failures that affect large areas of the mine, and, in extreme cases, sudden, violent bursts that eject coal or rock into the mine openings. Figure 2 shows that between 1995 and 2006, there was just one fatal coal burst at a retreat mine. However, on August 6, 2007, six miners were killed in a pillar failure that resulted in violent coal bursts and a mine collapse at the Crandall Canyon Mine near Price, Utah. Three would-be rescuers were killed in a second burst 10 days later. The MSHA report on the Crandall Canyon Mine incident (Gates et al., 2008) cited the cause of the mine collapse as a flawed pillar design, which allowed the stress level to "exceed the strength of a pillar or group of pillars near the pillar line,"[14] causing a local failure that triggered a widespread collapse. The report documented how the two pillar design software packages used to develop the design, the Analysis of Retreat Mining Pillar Stability (ARMPS) and LaModel, had been employed improperly.

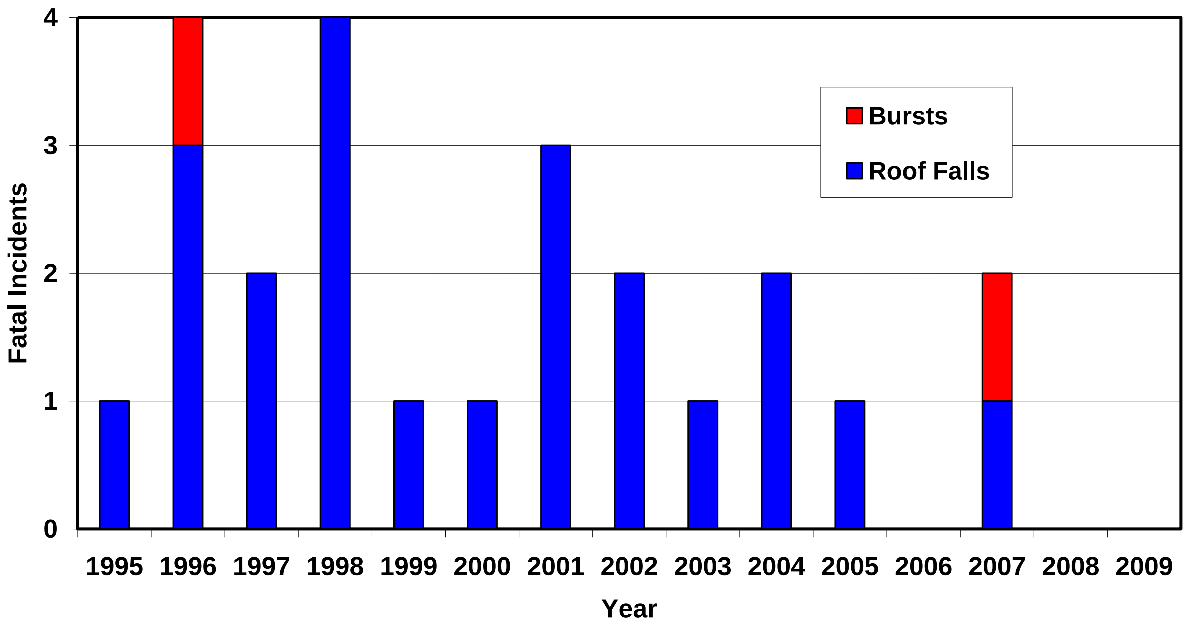

Figure 2. Fatal ground fall incidents during retreat mining, 1995-2009. Four of the fatal roof falls, and both bursts, were multi-fatality incidents.

Crandall Canyon was a former longwall mine whose coal reserves had largely been mined out. With cover that exceeded 2,200 ft at its deepest point, the retreat mining there was some of the deepest ever attempted in the U.S. The mining was being conducted within two former barrier pillars that were adjacent to extensive worked-out (gob) areas. The extreme pillar stresses, caused by the deep overburden and the large abutment loads[15] from the gob areas, combined to create a highly unusual situation that was particularly prone to pillar failure and coal bursts.

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[14] Fatal Underground Coal Burst Accidents, August 6 and 16, 2007. Report of Investigation. United States Department of Labor Mine Safety and Health Administration.
http://www.msha.gov/Fatals/2007/CrandallCanyon/CrandallCanyonreport.asp.

[15] An abutment load is created when some of the overburden weight which had been supported by the coal before it was mined out is transferred to the unmined coal adjacent to the gob (mined-out) area.

Purpose

In the FY 2008 Appropriation (Public Law 110-161), Congress directed NIOSH to:

> "conduct, in collaboration with the University of Utah and West Virginia University, a study of the recovery of coal pillars through retreat room-and-pillar mining practices in underground coal mines at depths greater than 1,500 ft. The study should examine the safety implications of retreat room-and-pillar mining practices, with emphasis on the impact of full or partial pillar extraction mining. The study should include, but not be limited to, analyses of:
>
> (1) The conditions under which retreat mining is used, including conditions relating to seam thickness; depth of cover; strength of the mine roof, pillars, and floor; and the susceptibility of the mine to seismic activity;
> (2) The procedures used to ensure miner safety during retreat mining.
>
> The report shall include recommendations to enhance the safety of miners working in underground coal mines where retreat mining in room-and-pillar operations is utilized. Among other things, the recommendations should identify means of adapting any practical technology to the mining environment to improve miner protections during mining at depths greater than 1,500 ft, and research needed to develop improved technology to improve miner protections during mining at such depths."

NIOSH was directed to submit a report, not later than 2 years after beginning the study, containing the results of the study to the Committees on Appropriations of the House of Representatives and the Senate.

Approach to the Study on Coal Pillar Recovery

The primary focus of this study was the safety of miners in room-and-pillar retreat mines recovering pillars at depths in excess of 1,500 ft. The most significant hazards faced by these miners are:

- Ground falls consisting of large "roof falls" (figure 3) that involve failure of the roof support, smaller "rock falls" (figure 4) that occur between roof supports, and "rib falls" (figure 5) that come from the side walls of the mine;
- Pillar failures that can affect large areas of a mine (figure 6), but are usually non-violent "squeezes" that occur slowly and seldom result in injuries to mine workers; and
- Coal bursts (figure 7), which are violent seismic events that cause coal to be ejected into the mine with enough energy to injure or kill miners.

Figure 3. A roof fall, at least 5 ft high, has blocked the entry. The timber supports were installed later.

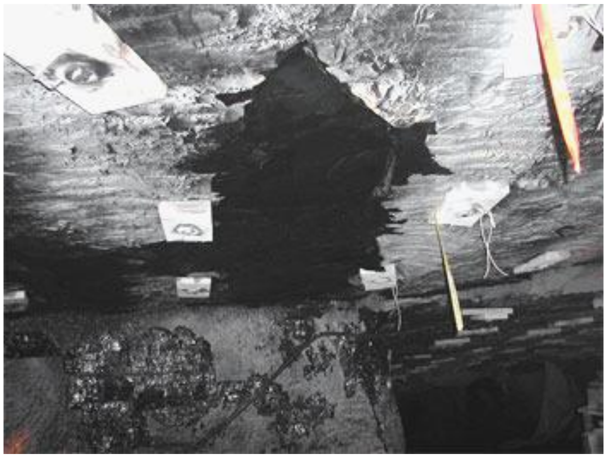

Figure 4. A piece of rock 4 ft wide, 10 ft long and just several inches thick has fallen from between the roof bolts. This rock fall resulted in a fatality.

Figure 5. A rib fall involving large blocks of rock and coal.

Figure 6. A pillar squeeze has resulted in closure of the mine entry and damage to the supports.

Figure 7. A coal burst has filled the mine entry with broken coal.

NIOSH determined early in the study that there are relatively few miners that work routinely at these depths, and that the hazards they face are not unique to the >1,500 ft depth. Miners recovering pillars at depths between 1,000 and 1,500 ft are also exposed to coal bursts and pillar failure, and all retreat miners are threatened by roof falls. Therefore, in order to fully evaluate these risks, it was necessary to broaden the study to include miners working in the 1,000-1,500 ft range.[16]

The study built upon extensive past NIOSH retreat mining research that included:

- The development and validation of the ARMPS pillar design software (Mark et al., 1997)
- The development of ARMPS design criteria specifically for deep cover pillar recovery (Chase et al., 2002)
- The initial development of the LaModel design software (Heasley, 1997)
- Performance evaluation and testing of Mobile Roof Supports for pillar recovery (Chase et al., 1997; Hay et al., 1997; Barczak and Gearhart, 1997)
- Design of the final stump[17] for safer pillar extraction (Mark and Zelanko, 2001)
- Enhancing roof bolt support and managing work procedures to minimize the risk of roof falls during pillar recovery (Mark and Zelanko, 2005)
- Application of special pillar recovery sequences to minimize the risk of bursts (Iannacchione and Zelanko, 1995; Iannacchione and Tadolini, 2008).

NIOSH also has extensive experience with techniques for monitoring mining-induced seismicity (Ellenberger et al., 2001; Swanson et al., 2008).

The first task was to identify the population of deep cover retreat mines. Coal mines in the U.S. regularly provide various types of information to MSHA and to the U.S. Department of Energy. However, this information does not include depth of cover nor whether the mine is recovering pillars. Indeed, this level of detail would be difficult to report and could be misleading. Much U.S. mining is conducted in areas of high topographic relief, and the depth of cover can change substantially over very short distances. For example, all of the mines that have recovered some pillars at depths in excess of 1,500 ft actually conduct much of their mining under lower cover. Similarly, mines may switch from development to retreat mining and back again within a single month, and a mine with several operating sections may be engaged in both simultaneously.

Fortunately, early in 2008, the Roof Control Supervisors in each MSHA District developed a list of the deeper cover retreat mines in their Districts, including their estimated maximum depths of cover, and MSHA shared this information with NIOSH. The list indicated that approximately 14 operating mines have experience recovering pillars at depths greater than 1,500 ft, and about 28 more have worked at depths in excess of 1,000 ft[18]. All of these mines are located either in the Central Appalachian coalfields of southern West Virginia, eastern Kentucky, and western

[16] For the remainder of this report, the term "deep cover" will refer to depths exceeding 1,000 ft, and "deepest cover" will be used to single out operations at depths in excess of 1,500 ft.
[17] The final stump is the last remaining part of the pillar after the rest of pillar has been mined.
[18] The numbers are approximate because several mines were idled or restarted during the 2-year duration of the study, and because of the variable topography issue described above.

Virginia, or in the states of Colorado and Utah. During the course of the study, NIOSH visited 30 of these mines, operated by 14 different coal companies (see figure 8).

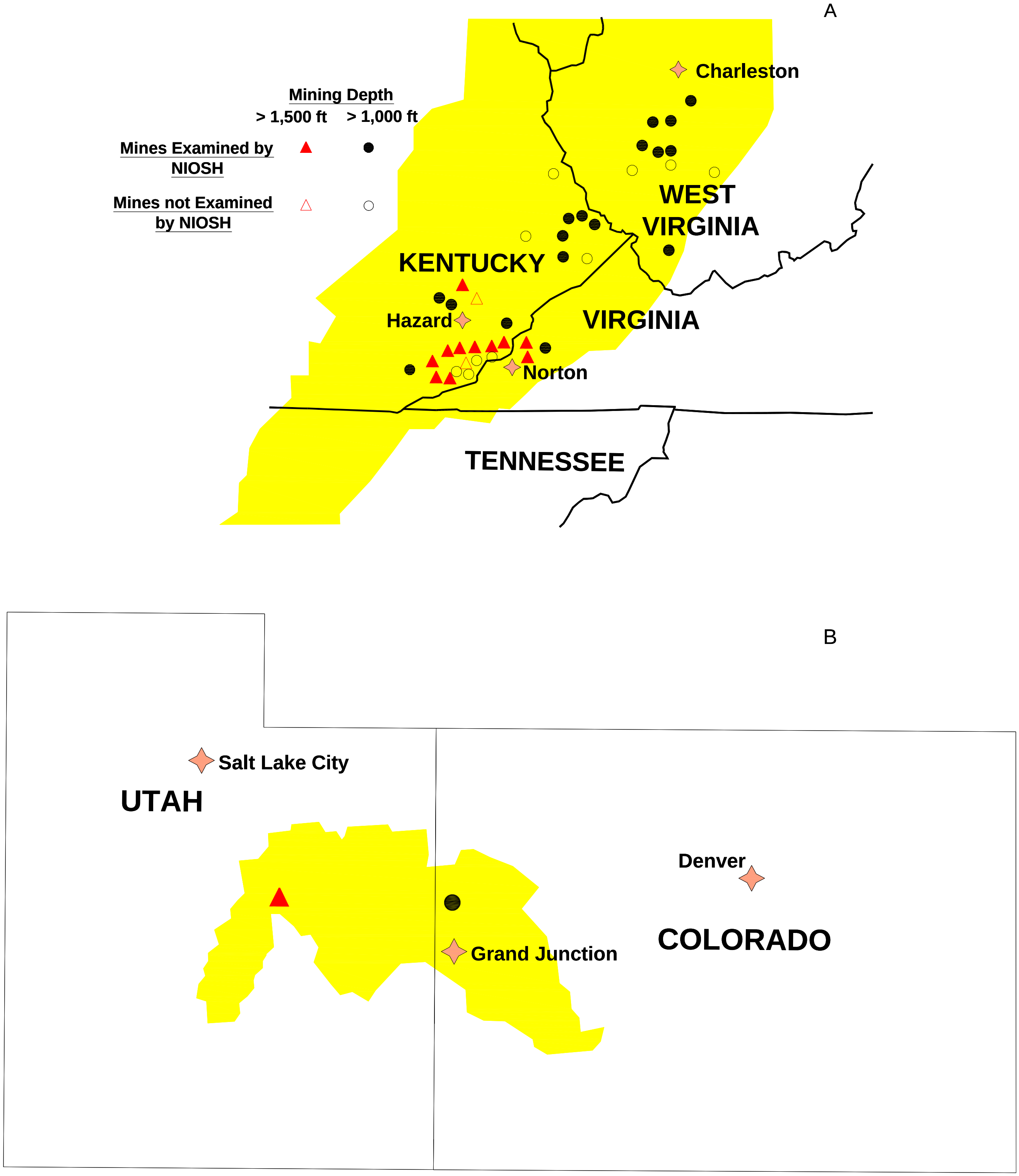

Figure 8. Location of the deep cover pillar recovery mines, 2008. Mines visited by NIOSH are noted. a) Central Appalachian deep cover retreat mines, b) Western deep cover retreat mines.

The goal of the mine visits was to obtain as much information as possible on the industry's experience with deep cover pillar recovery. At each mine, maps of active and past workings were reviewed with mining company officials who had first-hand experience with the conditions encountered. Every retreat panel where the depth of cover exceeded 1,000 ft was investigated, and the information that was obtained included:

- Pillar sizes, mining experience, and difficulties encountered;
- Cut sequences, stump sizes, roof supports, and other specifics of the extraction methods used;
- Roof geology, rock strength, and significant geologic features observed.

The mines also provided NIOSH with AutoCad map files, Roof Control Plans, geologic logs, rock mechanics data, and other information for subsequent analysis.[19]

Underground investigations were also conducted at 18 of the mines. While the historic deep cover sites were almost always inaccessible because they were mined out, it was often possible to observe current pillar recovery operations. Additional data on roof, floor, and coal geology was also collected underground.

By combining the information collected from the mines with data obtained from MSHA Roof Control Supervisors and the statistical data available in the MSHA accident and injury database, NIOSH obtained a detailed and current picture of the deep cover retreat mining segment of the industry, and how its safety performance compares with other segments. NIOSH was also able to evaluate current retreat mining practices and the degree to which the latest safety techniques are being employed. In addition, NIOSH facilitated Major Hazard Risk Assessments (MHRA) of deep cover pillar recovery operations at two cooperating coal mines.

The field studies and mine visits also provided more than 200 new retreat mining case histories for the ARMPS database. ARMPS is the NIOSH-developed software currently being used by the mining industry to size pillars for retreat mining. The ARMPS database includes both "successful" case histories, as well as ones that were "unsuccessful" due to pillar squeezes, major collapses, or coal bursts. ARMPS is already a critical mine safety technology, and since it is an empirical model, expanding the database enhances its accuracy and reliability.

Burst control was another focus of the NIOSH study. Since only two of the retreat mines that are currently operating have ever experienced a burst, this research emphasized the historical record. Using a variety of published and unpublished sources, a comprehensive list of large, multi-pillar burst events in retreat mines was created and analyzed. NIOSH researchers also visited Germany to study seismic monitoring and the other burst control technology employed in the extremely deep longwall mines[20] of the Ruhr coalfields.

[19] Under Federal Regulations, a mine operator is required to develop and submit to MSHA a Roof Control Plan suitable to the prevailing geological conditions and the mining system to be used at the mine (30 CFR 75.220(a)(1)).

[20] Typical German mines operate at depths in excess of 4,000 ft, while the deepest U.S. coal mine is under about 3,000 ft of cover.

Under contract with NIOSH, studies were also conducted by the University of Utah (U of Utah) and West Virginia University (WVU). At WVU, a team led by Prof. Keith Heasley focused on the LaModel numerical modeling program. LaModel is often used to design coal mine pillars where the mining geometry is too complex for the ARMPS technique. One key objective of the WVU project was to develop standardized best practice methods of calibrating LaModel so that its results are more closely tied to past experience. A detailed comparison of ARMPS and LaModel was conducted using more than 40 deep cover retreat mining case histories from 11 coal mines provided by NIOSH. The critical input parameters for LaModel were identified, and a number of new calibration procedures that make the program more effective were developed. A training manual was prepared that provides step-by-step directions and practical considerations so that mine planners can perform a fully calibrated LaModel analysis. The software itself was also modified and streamlined to incorporate the calibration techniques and improve the performance of the program.

The U of Utah effort, led by Prof. Kim McCarter and Prof. Walter Arabasz, concentrated on the application of seismic monitoring to reduce the risk of coal bursts. The project convened an Expert Panel on Seismic Monitoring Applicable to Deep Coal Mines to:

- Assess the current state of practice of seismic monitoring for underground mines;
- Evaluate and summarize the practical value of monitoring mining-induced seismicity (MIS);
- Evaluate the anticipated benefits of, and the potential difficulties with, seismic monitoring at different scales (from regional surface systems to detailed in-mine systems).

The panel included 16 national and international experts with backgrounds in both coal and metal mining. The panel participated in a workshop, held in Salt Lake City in October, 2008, and its input was used to prepare a guidance document. The U of Utah also held informational meetings for mining community stakeholders to report the results of the workshop. Other aspects of the U of Utah project resulted in the acquisition of two high-quality broadband monitoring stations to enhance the seismic monitoring capability in Utah's Wasatch Plateau-Book Cliffs coal mining region.

NIOSH also presented its proposed research plan to the Mine Safety and Health Research Advisory Committee (MSHRAC) during a MSHRAC meeting held in Pittsburgh in January, 2008. Several suggestions from MSHRAC were incorporated into the research.

Conditions under Which Retreat Mining is Used

The most recent evaluation of the size of the retreat mining sector of the U.S. underground coal industry was conducted in 2003.[21] That study concluded that approximately 10% of the underground coal mined in the U.S. came from retreat mining. The data also showed that more than 90% of the coal produced by pillar recovery came from the central Appalachian coalfields of southern West Virginia, Virginia, and eastern Kentucky. In this region, 75% of all room-and-pillar miners worked at retreat mines. The northern Appalachian coalfields were responsible for 8% of the retreat mining production, with most of it coming from northern West Virginia. Western mines contributed less than 2% of the total. There was essentially no pillar recovery taking place in Indiana, Illinois, western Kentucky, or Alabama. An analysis of the trends in coal production between 2001 and 2008 indicates that the contribution of retreat mining, and its geographic distribution, has likely not changed significantly during the interim.[22]

Depth of Cover

The size and location of the deep cover segment of the industry was evaluated using the list of deep cover mines obtained from MSHA in 2008. Statistics in the MSHA AIIE database indicate that of the approximately 39,000 underground coal miners in the U.S., about 900, or less than 3%, work in the deepest mines that have recovered pillars at depths greater than 1,500 ft (see tables 1 and 2). An additional 2,200 work at retreat mines at depths between 1,000 and 1,500 ft. Only one of the current deep cover pillar recovery mines has ever worked at depths exceeding 2,000 ft.

Table 1. Characteristics and injury record for deep cover retreat mines compared with other underground mines, average per year for the period 2006-2008.

Type of mine	No. of workers	Hours	Tons	No. mines	All injuries	Roof/rock fall injuries	Rib fall injuries	Reportable roof falls (non-injury)
Deepest cover retreat mines (greater than 1,500 ft)	898	2,282,045	7,099,244	14	92	11	8	51
Deep cover retreat mines (greater than 1,000 ft)	3,071	7,531,545	2,2582,391	42	330	52	24	127
All other room-and-pillar mines	21,712	47,511,378	157,083,701	548	1,781	289	50	1,114
All underground mines (all depths)	38,817	87,134,218	356,140,277	634	3,085	421	111	1,446

[21] In that study, NIOSH asked MSHA Roof Control Specialists and Supervisors from every MSHA District to provide information on pillar recovery practices in each of the mines they inspected. The information was then linked with the MSHA Accident Illness Injury and Employment (AIIE) database for the year 2001. In that year, U.S. underground mines produced 380 million tons of coal, 49.6% of which came from room-and-pillar mines. The retreat mines identified by the Roof Control Specialists produced 109 million tons, or about 58% of the total non-longwall production. Assuming that pillar recovery typically accounts for about one-third of the production at these room-and-pillar mines, then about 35 million tons, or 10% of all underground production, came from pillar recovery.

[22] Miners in central Appalachian room-and-pillar operations, where 90% of retreat mining takes place, accounted for 42% of all underground hours worked in 2001, and 41% in 2008.

Table 2. Injury rates for deep cover retreat mines compared with other underground mines, averaged for 2006-2008. All rates per 200,000 hours worked.

Type of mine	All injury rate	Roof/rock fall injury rate	Rib fall injury rate	Combined ground fall injury rate	Reportable roof fall rate
Deepest cover mines (greater than 1,500 ft)	8.09	0.93	0.70	1.64	4.47
Deep cover mines (greater than 1,000 ft)	8.76	1.38	0.65	2.03	3.37
All other room-and-pillar mines	7.50	1.22	0.21	1.44	4.69
All underground mines (all depths)	7.08	0.97	0.25	1.23	3.32

The data collected during the current study indicate that at the typical deep cover retreat mine, at least 50% of the pillar extraction is conducted beneath cover that is less than 1,000 ft. Considering also that only about one-third of the production from these mines comes from pillar recovery, it seems likely that total exposure of miners to pillar recovery operations at depths greater than 1,500 ft is less than ½ of one percent of all hours worked underground.

Figure 9 shows the geographic distribution of the hours worked in deep cover retreat mines. There is apparently no deep cover pillar recovery at all in the Northern Appalachian, Illinois, or Alabama coal regions. Of the 14 deepest cover retreat mines, eight are located in Harlan County, Kentucky. Five others are in the neighboring counties of Perry in Kentucky and Wise in Virginia, and one is in Utah. Of the 28 other active mines with pillar recovery experience at depths greater than 1,000 ft, 27 are located throughout eastern Kentucky, southern West Virginia, and western Virginia, and one is in Colorado. Two longwall mines (in addition to Crandall Canyon), one in the west and the other in the east, have also recently recovered pillars prior to abandoning a worked-out seam.

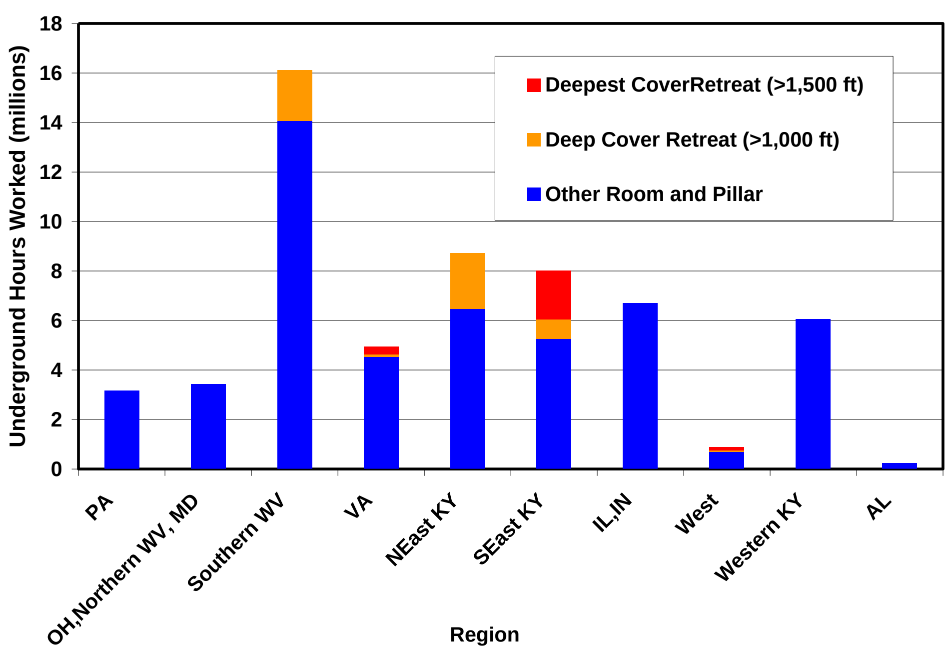

Figure 9. Geographic distribution of the hours worked in room-and pillar mines in 2008.

Mining Methods Employed

All room-and-pillar mines in the U.S. employ continuous mining machines, operated by remote control, to cut the coal from the face. In most mines, these machines simultaneously load the coal onto rubber-tired shuttle cars or battery haulers that carry the coal to a conveyor belt. Of the 30 active deep cover retreat mines that were visited during this study, 26 employed this mining system. The four exceptions, all located in Kentucky, employed continuous haulage systems, instead of rubber-tired haulers, in the thinner seams that they were mining.

The deep cover retreat mines typically drive five to nine parallel tunnels (entries) when they develop a panel (figure 10). Barrier pillars are almost always left between panels for both ventilation purposes[23] and ground control. Among the group of mines working under deep cover, it is very unusual to widen the panel by driving rooms into the barrier after the panel is developed.[24]

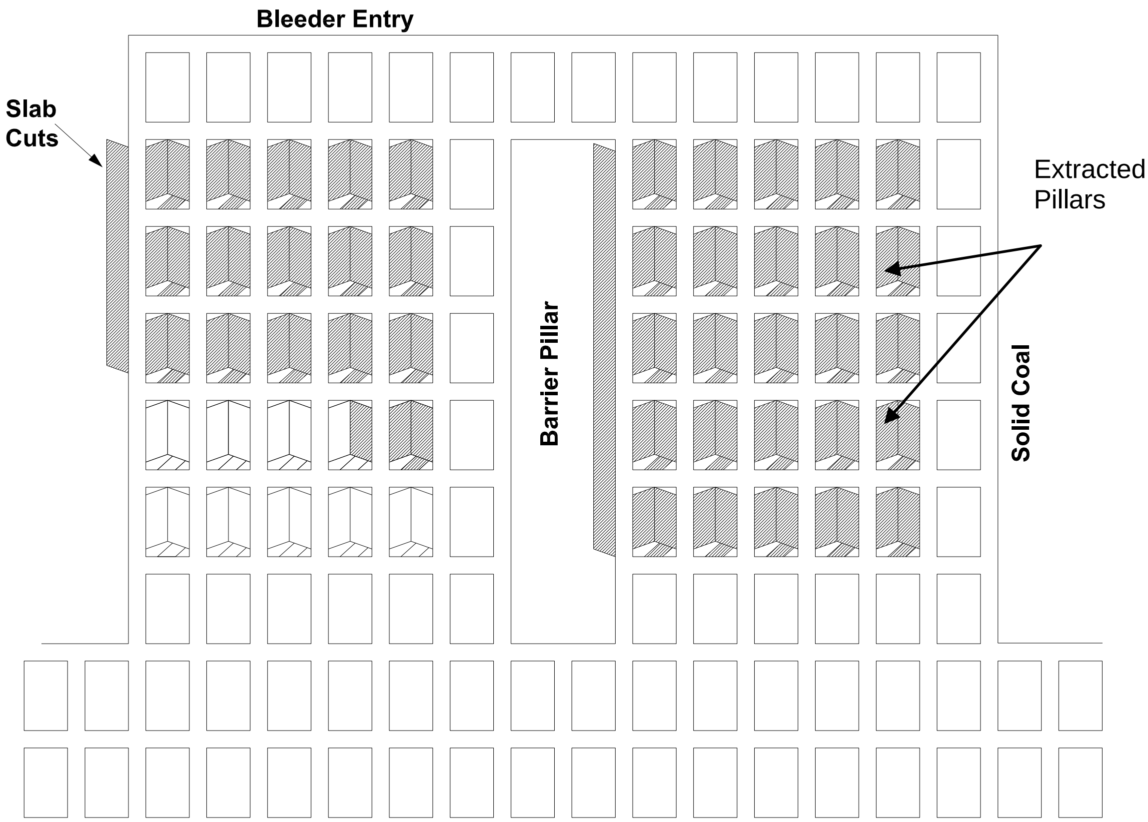

Figure 10. Retreat room-and-pillar mining layout, showing the panel on the left side in the process of being extracted. The right-side panel has been previously extracted (mined out), and a barrier pillar separates the two panels.

[23] Barrier pillars isolate the previously mined panel from the current panel, thereby keeping out dangerous gasses and making the current panel easier to ventilate.

[24] In some mining plans, very wide barriers are initially left between the new and the old panel while the new panel is being developed. Then, while the new panel is being retreated, rooms are driven into the barrier, creating pillars which are then recovered. A detailed discussion of this technique can be found in Chase et al., 2002.

Once the panel has been fully developed, retreat mining usually begins at the panel's furthest point into the mine. One row of pillars is usually left at the back end of the panel for bleeder entries,[25] and for the same reason it is increasingly common to leave a row of pillars along one side of the panel (see figure 10).

Mines that use rubber-tired haulage generally start mining a row of pillars by extracting the pillar near the adjacent mined-out panel. For operational reasons, the continuous haulage mines typically prefer to "close in the center," taking their last lifts from the pillars adjacent to the belt entry near the middle section of the panel. Most of the mines take slab cuts from the barriers as they retreat, but they do not completely remove the barriers (figure 10).

Historically, a wide variety of cut sequences have been employed to extract the individual pillars. Because today's remote-controlled continuous miners can take deeper cuts, most mines prefer to extract the pillars entirely from the previously developed entries. These methods can be classified as either (1) "left-right" (also called "Christmas tree mining" or "twinning"), in which lifts are taken on both sides of the entry, or as (2) "outside lift," in which cuts are taken on just one side (see figure 11a and 11b). A NIOSH study (Mark et al., 2003) estimated that, nationally, about 60% of all retreat mines used left-right techniques, and 35% used outside lifts. Among the deep cover retreat mines visited for the current study, left-right plans were even more popular, used by 28 of the 30 mines. The exceptions were two of the continuous haulage mines that employed outside lifts.

"*Split and fender"* plans can be used when the pillars are so large that they cannot be fully recovered by lifts taken from the entries (figure 11c). Instead, a "split" is extracted from the middle of the pillar, which cuts the original pillar in half and creates two thin pillars (the "fenders"). Before the fenders can be extracted, the roof in the split must be bolted, which is time-consuming and exposes the roof bolt operators to additional hazards. In spite of the fact that deeper cover usually means larger pillars, just one of the mines in this study routinely employed split and fender techniques. In some cases, left-right plans were even used to extract pillars as large as 75 by 75 ft (95 by 95 ft), even though a 20-ft wide fender of coal had to be left down the center of the pillar because the lifts could not reach the pillar center.

[25] Unless they are sealed, worked-out gob areas in mines must be ventilated to prevent the build-up of dangerous gasses. This is accomplished with "bleeder entries" that surround the perimeter of the gob (mined out) area. The bleeder entries must be checked periodically to ensure that the airflow has not been choked off by a roof fall or other blockage.

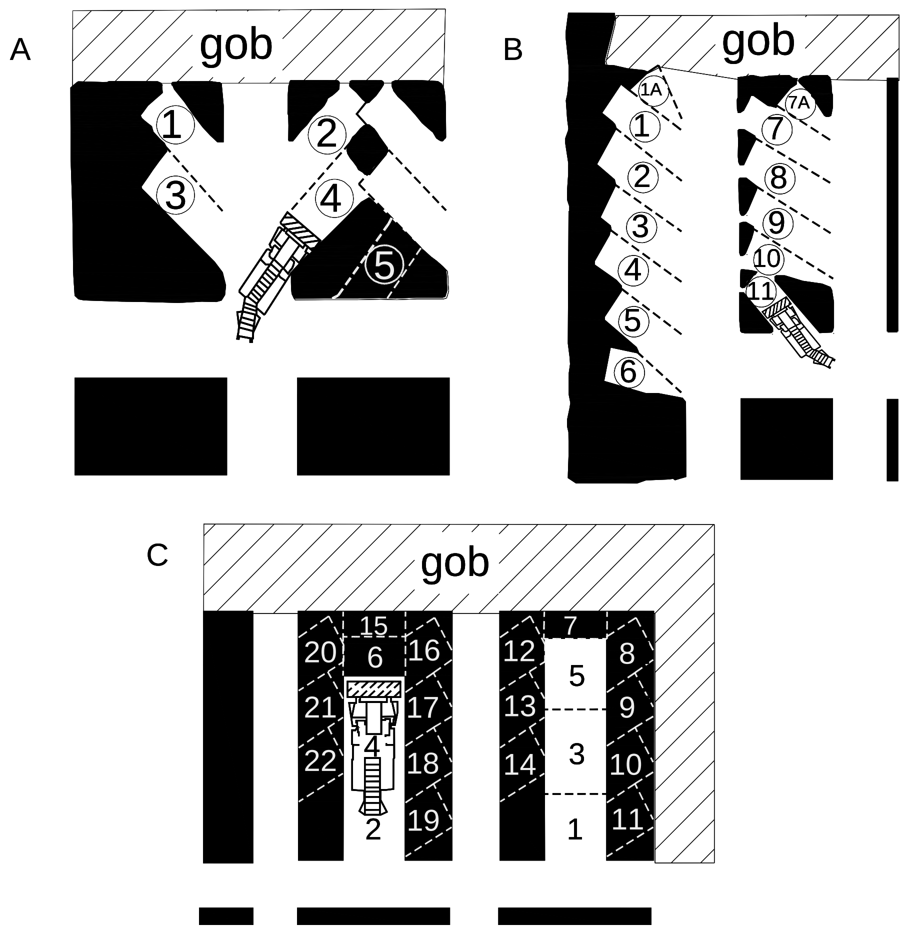

Figure 11. Cut sequences used to extract individual pillars: (a) Christmas tree, showing cuts taken from the entry, and planned cut no. five from the crosscut, (b) Outside lift, showing slab cuts taken from the barrier, and (c) Split-and-fender.

Roof and Floor Strength

Previous studies have found that rock surrounding the coal seams in the Central Appalachian, Utah, and Central Colorado coalfields is stronger than the rock in other U.S. coalfields (Rusnak and Mark, 2000; Mark, 2007). Observations in the deep cover retreat mines conform to this trend. The lowest Coal Mine Roof Rating (CMRR)[26] values measured were approximately 45, which is considered to be at the lower end of the "intermediate" strength range. The typical roof at most of the mines had CMRR values in the 50s. Only six mines had typical roof conditions that would be considered "strong," with a CMRR greater than 60. None of the mines that were visited reported problems with massive sandstone roof that was difficult to cave.[27]

[26] The CMRR is an engineering rock mass rating system developed for coal mines. It grades the immediate roof above the mine opening on a zero to 100 scale, considering such factors as the compressive strength of the rock, the degree of bedding, and the presence of fractures and other natural weakness planes (Mark and Molinda, 2007).

[27] An extreme example of a mine with unsatisfactory caving was described in Newman (2008). At that mine, pillars were extracted from an area measuring 650 ft by 2,000 ft without a significant collapse of the main roof. Concerns about the potential for a large roof collapse, possibly accompanied by coal bursts and an airblast, led to the decision to abandon retreat mining in the panel. This mine was located in Harlan County, KY.

The relatively light primary roof support systems that most of these mines employ provide further evidence of the relatively competent immediate roof conditions. More than 80% of the deep cover mines employ 4- or 5-ft, fully-grouted bolts as primary support, and supplemental support is seldom required except during retreat. MSHA statistics also indicate that, despite the higher stresses associated with their depth, the rate of unplanned, non-injury roof falls[28] is about 28% lower in the deep cover mines than in other room-and-pillar mines (table 2).

The overburden is also relatively competent, typically consisting largely of sandstones and siltstones. Usually there are some particularly massive, strong, and thick sandstone units, as travelers can see in the exposed outcrops in the Western coalfields or in the spectacular highway road cuts of central Appalachia.

Despite the trends described above, the geology of both the immediate and the main roof above any individual mine is subject to significant variation. Major sandstone channels that are present near the coal seam can be particularly troublesome. The margins of such channels have been associated with roof falls, while the channels themselves have contributed to bursts (Hoelle, 2008). The location of channels and other similar geologic features can be difficult to predict, because they are often only several hundred ft wide, while exploratory boreholes are typically spaced thousands of feet apart.

Faults, along which there has been some rock movement some time in the geologic past, are also prevalent throughout the coalfields. Some are difficult for even the trained eye to discern, while others may have shifted the strata by hundreds of feet. Mining that triggers new movement along a pre-existing fault can be one source of coal bursts. Unfortunately, usually only the larger faults are known before they are encountered underground.

The floor rocks in the West and in Central Appalachia tend to be firm, and groundwater is seldom a major issue in U.S. coal mines that are deeper than 1,000 ft. On the other hand, multiple seam interactions are an important concern at a large majority of the deep cover retreat mine operations. Almost 80% encounter workings less than 200 ft above or below their active mining. Multiple seam interactions can increase the likelihood of roof falls, pillar failures, and bursts (Mark, 2007). Fortunately, most multiple seam interactions occur in relatively small and well-defined areas that can be predicted in advance. To minimize their impact, mines can install extra support, narrow their entry spans, lengthen their pillars, or avoid the area entirely (Mark et al., 2007).

Seam Thickness and Coal Strength

The seam thickness at 87% of the mines NIOSH visited during the current study was between 5 and 8 ft. Figure 12 shows the distribution of seam heights.

[28] Unplanned roof falls are falls that did not cause an injury, but are reported to MSHA because they occurred in the active workings and either extended above the anchorage zone of the roof bolts, impaired ventilation, or impeded passage (30 CFR 50.2 (h) (8)).

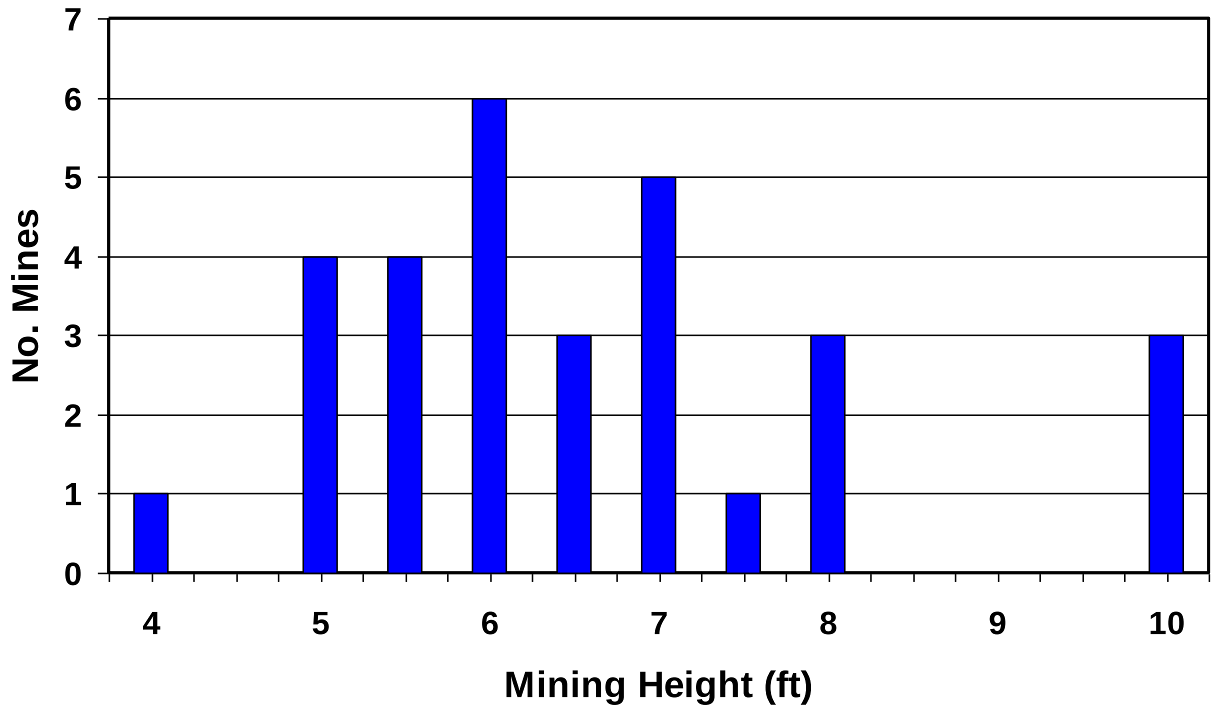

Figure 12. Histogram showing the distribution of seam heights of 30 deep cover retreat mines visited by NIOSH.

Three of the mines, all in the east, are mining two seams simultaneously. When both seams are mined together, along with the 3-5-ft-thick rock parting that separates them, 10-15-ft-high openings are created. To minimize their exposure to the high ribs, one of the twin-seam mines extracts only the top seam and the parting during development. Then the bottom seam is recovered by mining the floor in the entries when the pillars are recovered during retreat. This floor mining sequence has the additional advantage that smaller pillars can be used, because of the reduced width-to-height ratios for the intact pillars outby the pillar line.

Pillar strength is a parameter that is very difficult to measure. The "classic" approach was to test the uniaxial compressive strength (UCS) of small specimens in the laboratory, but this approach was discredited by a comprehensive study, involving 4,000 individual UCS test results from over 60 coal seams, which found that there was no correlation with full-scale pillar strength (Mark and Barton, 1997). It seems likely that UCS tests on small samples actually measure the degree of coal cleating, while pillar strength is determined by large-scale geologic features such as bedding planes, clay bands, rock partings, and interfaces with roof and floor rock (Mark, 2006).

On the other hand, studies from around the world have indicated that the affected pillar strength may not vary significantly from region to region. Empirical pillar strength formulas have been developed and used successfully for decades in South Africa, Australia, and the U.S. without accounting for variations in strength between individual coal seams (Salamon, 1992; Galvin et al; 1999; Mark, 2006).

Coal strength also does not seem to play an important role in determining whether or not a mine is burst-prone. Iannacchione and Zelanko (1995) noted that bursts have occurred in at least 25 different U.S. coalbeds, varying from strong, blocky seams to the very friable Pocahontas No. 3 and No. 4 seams. Laboratory studies conducted by Babcock and Bickle (1984) showed that most coals can fail violently if they are highly stressed and the confinement is suddenly reduced. Extensive German laboratory studies using large-scale specimens have also concluded that nearly all bituminous coals can burst. In these experiments, coal seams ranging in unconfined compressive strength from 700 psi to 7,000 psi have all been shown to be burst-prone (Bräuner, 1994).

Susceptibility of Mines to Seismic Activity

Coal bursts are defined as the sudden, violent ejection of coal or rock into the mine opening. They have long been among the most feared hazards in deep retreat mines. As long ago as 1935, Rice 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).

Fortunately, in recent times bursts have been rare events in retreat mines. There have been no bursts in room-and-pillar mines since the events at Crandall Canyon in 2007, [29] and only two room-and-pillar mines in operation today have ever experienced a burst.

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 are not alone in this regard. Natural seismic events (earthquakes) have been the subject of much larger research efforts, but the science of earthquake prediction is still in its infancy.

Some valuable generalizations can be made, however. First and foremost, high stress is a universal feature of burst-prone conditions. Deep cover is the primary source of high stress, but stress levels can be further increased by the abutment loads that are created by retreat mining, or by multiple seam interactions. Because minimizing the stress is so important, pillar design is probably the most important burst prevention technique. Pillar design will be discussed further in later sections of this report.

Geologic factors also contribute to burst proneness. The presence of strong, massive sandstone near the seam has often been noted where bursts have occurred (Maleki, 1995; Iannacchione and Zelanko, 1995; Bräuner, 1994). While some local guidelines have been established, no generic "signature" of burst-prone geology has ever been established.

As long ago as the early 1930s, bursts were classified into two types according to their cause (Rice, 1935). "Pressure bursts" were thought to originate in the seam itself, and to be associated with high stress. "Shock bursts," on the other hand, were thought to be caused by "the breaking of a thick, massive, rigid strata at a considerable distance above the coal bed, causing a great,

[29] In addition to the events at Crandall Canyon, 27 bursts were reported to MSHA during 2007-2008. All of them occurred at longwall mines located in Utah or Colorado.

hammerlike blow to be given to the immediate roof of the mine opening, which it transmits as a shock wave to the coal pillar or pillars" (Rice, 1935).[30]
The distinction between "shock" and "pressure" bursts is still useful, though many bursts may combine elements of both. In Poland, bursts are divided into "mining events" of low magnitude, and "regional" events of high magnitude that are often associated with fault zones (Mutke and Stec, 1997). In Germany, most of the hazardous bursts underground have been associated with localized high stresses in the seam. These rockbursts release relatively little seismic energy, but they are hazardous because they occur so close to the working face (Bräuner, 1994).

Mining activity apparently can trigger bursts by removing the *confinement* for coal that is highly stressed. For example, because the coal near the edges of a heavily loaded pillar is normally in a yielded state, the greatest stress levels are found in the pillar core, close to the center of the pillar. The situation is normally stable because the yielded coal near the rib provides confinement to the highly stressed coal in the core. However, when the coal near the rib is mined, which happens as the pillar is being extracted, the confinement is removed. Usually the highly stressed coal then yields gradually, but in some circumstances it can fail suddenly and violently in a coal burst. Pillar splitting, which removes the coal that is in the most highly stressed part of the pillar core, is an activity that historically has been particularly likely to cause bursting (Holland, 1958).

The role of confinement in triggering bursts helps explain why studies and experience have found that, other factors being the same, room-and-pillar retreat mining is more burst-prone than longwall mining (Maleki et al., 1999). With the longwall method, thin slices of coal are taken from the edge of the very large longwall block, giving the coal time to yield gently while the stresses move deeper into the un-mined block. The pillar recovery process, in contrast, requires that the coal rapidly transition from a high to a low stress state, which can result in a burst. One mine in Colorado provided a valuable side-by-side comparison of the two methods. After suffering a number of damaging bursts while conducting pillar recovery at depths that reached 2,100 ft, the mine decided to switch to the longwall method. Although bursts were not entirely eliminated, conditions improved significantly and the mine was able to successfully extract the remaining coal reserve.

Most mining-induced seismicity is not generated in the coal seam, but rather in the overburden as it caves and subsides. Moreover, only a tiny fraction of mining-induced seismic events are associated with coal bursts. As an illustration, German seismic monitoring stations recorded 4,623 mining-induced events over one 10-year period, but only 18 coal bursts occurred in the mines during that same period (Bräuner, 1994). In fact, even very large events may have little impact on the mine if they occur well above the workings, such as the magnitude 4.2 event that was located approximately 500 ft above the Willow Creek longwall mine in Utah, but did not result in a coal burst at the mining horizon (Ellenberger et al., 2001). During one 5-year period in Poland, there were 15 large mining-induced events with magnitudes ranging from 2.2 to 4.0.

[30] Today, we understand that the sudden, dynamic failure in the overlying (or underlying) strata releases elastic energy in the form of seismic waves. The failures include sudden downward movements of the rock above the worked-out areas, shear slip motion on rock fractures in the overburden, or some combination of these two mechanisms (Pankow et al., 2008). Shear slip motion can occur on newly created fractures, or on reactivated pre-existing faults (Swanson et al., 2008, Alber and Fritschen, 2008). The seismic energy released by such events can cause damage both underground and on the surface.

Only six of these had any effect underground (Mutke and Stec, 1997). Seam level “mining tremors,” on the other hand, are often too small to register on a regional seismic network, but they can result in a serious injury if a miner is in the vicinity of the seismic events.

In order to fully evaluate the magnitude of the seismic risk in deep cover retreat mines, NIOSH undertook to catalog the bursts that have been documented during the past 25 years. Coal mines are required to report to MSHA all occupational injuries and any “accident” that involves “A coal or rock outburst that causes withdrawal of miners or which disrupts regular mining activity for more than one hour” (30-CFR50.2h9). However, since there is no special coding for “outburst,” NIOSH identified the burst-related injuries and accidents within the AIIE database by searching the narratives that are included with each report, using keywords such as “burst,” “bounce,” and “outburst.” The narratives were then carefully screened to remove all but those cases that clearly referred to a violent ejection of coal or rock. In all, 89 reported burst events in room-and-pillar mines were identified for the period 1983-2008.

Unfortunately, as the investigation of the Crandall Canyon Mine disaster showed (Gates et al., 2008), a non-injury outburst can go unreported even if it does meet the criteria set by the CFR. To complete its database, NIOSH combed the technical literature, held discussions with MSHA Roof Control Specialists and industry personnel, and reviewed numerous mine histories. This extensive survey revealed just four substantial likely burst events that were not in the MSHA database. Therefore, NIOSH is reasonably confident that major coal bursts that cause substantial damage underground are unusual events and are likely to have been reported.[31]

The final list contains 93 burst events that occurred in room-and-pillar mines between 1983 and 2008. These occurred at a total of 39 individual mines, or less than 1% of the room-and-pillar mines that operated during this period. [32]

The geographic distribution of the bursts included in the list is also striking. About half of the mines that have had bursts have been located in either Utah or west-central Colorado. These 19 mines also represent about 50% of all the room-and-pillar mines that operated in those coalfields during the time period. Harlan County is the most burst-prone area in the east, but even there only six mines reported bursts during this period, out of more than 250 room-and-pillar mines that were active. The 14 remaining mines that reported bursts are scattered among more than four thousand others in central Appalachia. Bursts have been entirely unknown in the northern Appalachian and Illinois Basins.[33]

[31] Incidents that involve fatalities are obviously the subject of thorough MSHA investigations, but many other incidents have been investigated by Roof Control Specialists from MSHA Technical Support (see, for example, Gauna and Phillipson, 2008). The published literature also includes accounts of significant incidents prepared by consultants, researchers, and industry experts. Often, several sources have described the same event.

[32] NIOSH created a list of room-and-pillar mines, by state and county, from the MSHA AIIE database. The list includes all underground, non-longwall mines that produced at least 10,000 tons in any one year between 1983 and 2008. There were more than 5,000 mines that met these criteria.

[33] Internationally, it is worth noting that no known bursts have occurred in coal mines in Australia or South Africa, and they are exceedingly rare in the UK and India (Sheorey et al., 1997). On the other hand, China, Germany, Poland, the Czech Republic, and other eastern European coal-producing countries have long histories of burst control (Li et al., 2007; Holub, 2007; Baltz and Hucke, 2008).

If the relatively small number of room-and-pillar mines with burst experience is striking, so is the relatively small number of bursts at each of them. Fourteen of the mines on the list accounted for 59 bursts, while 28 mines had just one burst each. But even the mines classified as "burst-prone" often apparently operate for years without encountering a burst. Where several bursts are reported at the same mine, there appears to be a tendency for bursts to cluster in distinct areas, indicating that geologic factors are important.

At least two of the mines on the list struggled with persistent bursting, and eventually each one had to abandon several panels before moving to less burst-prone areas. At these mines, the bursts were "predictable" in that they were most intense during particular cuts taken from particular pillars. One of these mines solved the problem by moving to an area where the geology was determined to be less burst-prone, while the other abandoned pillar recovery and shifted to the longwall mining method.

The incidence of bursts in room-and-pillar mines has also decreased significantly with time. Figure 13 shows that half of the bursts in the list occurred in late 1980s, when there were about eight bursts per year. During the decade of the 1990s, the burst rate fell to three per year. There have been just 13 bursts in this decade. A number of factors have likely contributed to the reduced number of bursts, including:

- Longwall mines have almost entirely replaced room-and-pillar mines in the burst-prone Western coalfields;
- Major research efforts during the 1980s and 1990s resulted in better mine design for burst control;
- Mining companies and regulatory agencies have acted to aggressively reduce the risk of bursts where bursts have occurred, using technologies that will be discussed in a later section of this report.

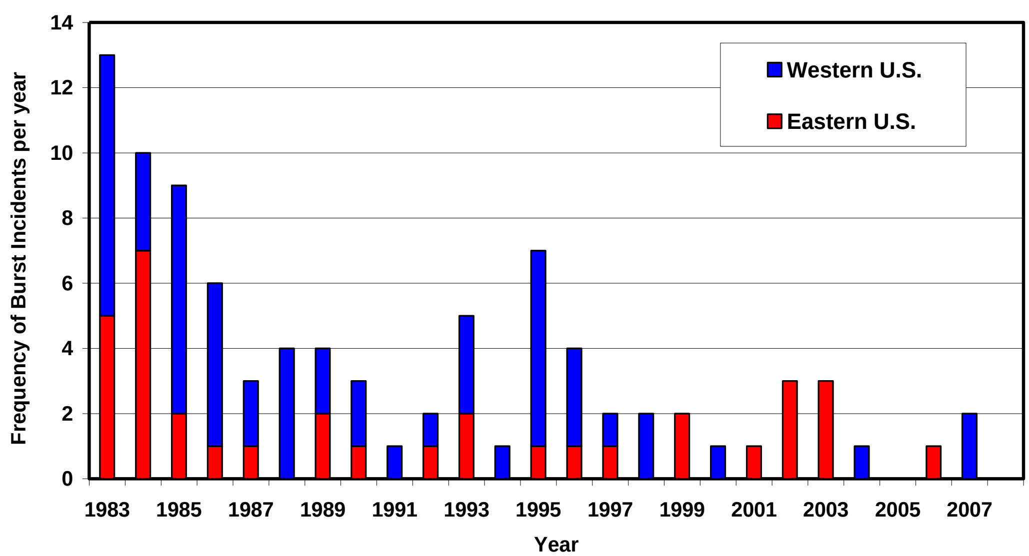

Figure 13. Historical trend in the occurrence of coal bursts in room-and-pillar mining, 1983-2008.

Only two currently active room-and-pillar retreat mines, one in Harlan County and the other in southern West Virginia, have ever reported bursts.

The incidence of bursting also seems to increase as the depth of cover increases. Analysis of the ARMPS database shows that for case histories where the depth of cover was less than 1,500 ft, only 2% encountered bursts. For the handful of cases where the depth of cover exceeded 2,000 ft, however, almost half encountered bursts (figure 14).

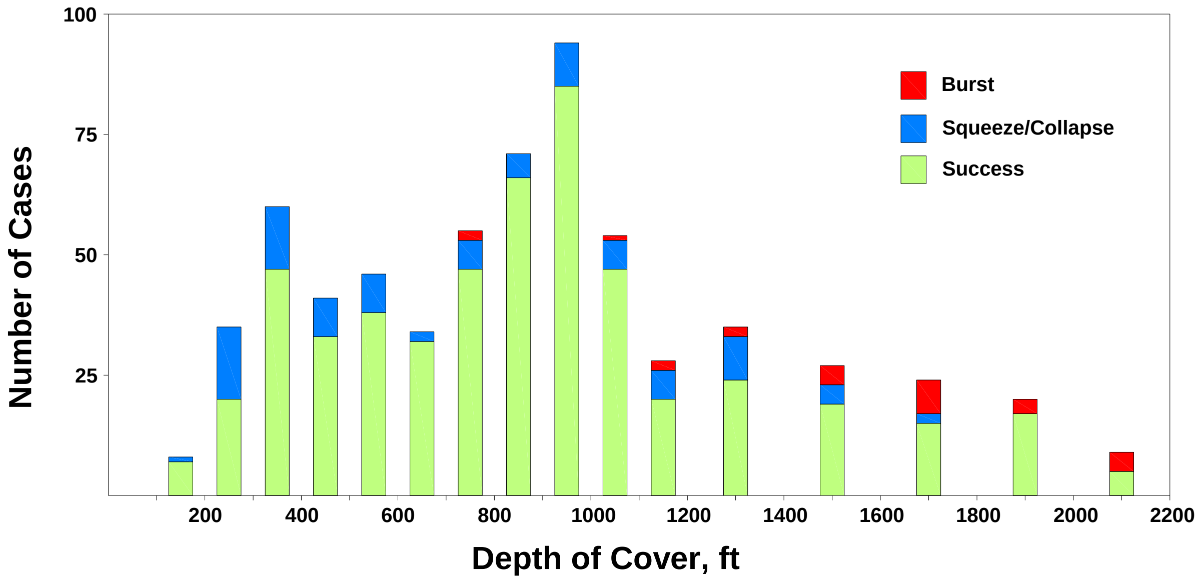

Figure 14. Distribution of pillar failures and pillar bursts with depth in the ARMPS database.

NIOSH singled out for special study 17 large burst events that resulted in extensive damage to at least several pillars. By far, the largest event in this group was the disaster at Crandall Canyon, which affected hundreds of pillars over a very large area. Three other fatal incidents (two from 1983 and one in 1996) were also multi-pillar bursts. The 17 events occurred at just 14 different room-and-pillar mines during the past quarter of a century.[34] Nine of these mines have been located in Utah, west-central Colorado, or Harlan County, KY. The other five mines, with one large burst apiece, were scattered around southern West Virginia.

Analysis indicates that 12 of the 17 multi-pillar bursts, including all of those that resulted in fatalities, can be attributed to inadequate pillar design. All 12 of these events occurred during retreat mining**.** *In nine instances, the barrier pillars were too small, were being extracted on retreat, or were not used at all.* In five of the 12 cases, pillar splitting operations without a barrier pillar apparently triggered the multi-pillar burst. In one other case (from 1991), there is not enough information to quantitatively evaluate the pillar design.

[34] It is worth noting that the MSHA database also indicates that development sections at almost every longwall mine in Utah and the North Fork Valley of Colorado have experienced injuries caused by small bursts.

The remaining four multi-pillar bursts, occurring at two different mines, are less easily classified. These bursts occurred in areas that would not have been considered high risk based on their mine design. For example, the incident described by Gauna and Phillipson (2008) occurred in a seam in West Virginia that had never had a burst, on a development section, beneath old works that had not been retreat mined. Yet this same mine has extensive burst-free experience recovering pillars under similar depths of cover beneath a variety of highly stressed upper seam remnants. The incidents described by Newman (2002) occurred in a Kentucky mine during development beneath first workings that would normally not have been considered high risk. The case of the Colorado longwall mine described by Swanson et al. (2008) and Maleki et al. (2009) involved a similar multi-seam scenario. In this last instance, however, the heaviest damage was centered not even at the development faces, but in an area of steeply dipping faults several hundred feet outby. Fortunately, none of these events resulted in injury to personnel.

It may be significant that most of the multi-pillar bursts occurred in mines that have also had small bursts that resulted in injuries. It seems that small bursts, whether they result in injuries or not, may be a valuable indicator of the potential for larger bursts. Whyatt (2008) showed that in western longwall mines, an increased frequency of small bursts has often foreshadowed a larger event.

EVALUATION OF PROCEDURES AND TECHNOLOGIES USED TO ENSURE MINER SAFETY

NIOSH evaluated a wide range of procedures and technologies that are used to protect miners from the hazards of retreat mining. *Engineering* procedures include all aspects of mine planning, including layout, pillar design, support selection, and selection of mining sequence. Because proper planning can reduce or eliminate risks before miners are ever exposed to them, engineering procedures are generally the key to retreat mining safety.

Administrative and *Training* procedures are used to limit the exposure of personnel to hazards. They are generally less effective than engineering procedures, because the retreat mining process requires that miners be located 20-40 ft from where the coal is being cut, even when equipment is operated by remote control. Unlike longwall mining, retreat mining is not amenable to automation. The necessary proximity of miners to potentially large sources of hazardous energy releases, like roof falls or coal bursts, also minimizes the value of *Personal Protective Equipment* procedures.

Statutory procedures for retreat mining are included in Part 75, Title 30 of the Code of Federal Regulations (30 CFR 75). The regulations that specifically address retreat mining[35] have not been updated in several decades, and therefore they do not cover many of the new procedures and technologies that are discussed in the following sections of this report. The CFR does contain some general regulations which pertain to retreat mining, including:

- 30 CFR § 75.220(a)(1) Each mine operator shall develop and follow a roof control plan, approved by the District Manager, that is suitable to the prevailing geological conditions, and the mining system to be used at the mine. Additional measures shall be taken to protect persons if unusual hazards are encountered.

- 30 CFR § 75.203(a) The method of mining shall not expose any person to hazards caused by excessive widths of rooms, crosscuts and entries, or faulty pillar recovery methods. Pillar dimensions shall be compatible with effective control of the roof, face and ribs and coal or rock bursts.

- 30 CFR § 75.202(a) The roof, face and ribs of areas where persons work or travel shall be supported or otherwise controlled to protect persons from hazards related to falls of the roof, face or ribs and coal or rock bursts.

Over the years, these regulations have helped new procedures and technologies to be incorporated into retreat mining practice once they have demonstrated their effectiveness in protecting retreat miners.

Roof supports, including rock bolts, cable bolts, and Mobile Roof Supports, are the technologies that are most important to retreat mining safety. Some stability monitoring and warning devices

[35] The two most relevant of these are Section 75.207, "Pillar Recovery, and Section 75.222.d, "Roof Control Plan approval-criteria."

have been proposed over the years (for example, see Maleki and McVey, 1988), but none have ever proved to be effective. Retreat mining is conducted in such a wide range of geologic conditions, and those conditions can change so rapidly, that it would be unreasonable to expect any single technology to provide reliable protection in all circumstances.

The following sections discuss the procedures and technology available to protect miners from each of the main hazards of retreat mining.

Prevention of Ground Falls

Roof falls have been responsible for the deaths of more retreat miners than any other single cause. During pillar extraction, adequate roof support must be in place to ensure that premature caving does not cause a roof fall to occur until after the miners have completed their work and left the area. In the 15 years since 1994, there have been 22 fatal roof falls during retreat mining that have resulted in a total of 26 deaths. Four of these fatal roof falls have occurred at depths exceeding 1,000 ft.

Studies conducted by NIOSH in the late 90s and early part of this decade focused on the factors contributing to fatal roof falls (Mark et al., 2003). The conclusion was that, although the mines had in most cases been following their Roof Control Plans, the roof support had not been sufficient to protect the miners. Three key technologies for improving the level of roof support were identified:

- Leaving an engineered final stump, rather than extracting the entire pillar (figure 15);
- Substituting mechanized Mobile Roof Supports (MRS, see figure 16) for traditional wood timbers;
- Using longer and stronger roof bolts on retreat sections, particularly in intersections.

Subsequently, NIOSH, MSHA, state regulatory agencies, and the mining companies made concerted efforts to implement these technologies into retreat mining practice. In fact, the past four years have seen just one fatal roof fall on a pillar line, compared with an average of two per year during the previous decade.

One of the goals of the current study was to determine the degree to which these three technologies have been adopted by the deep cover mines. The evaluation was based on the MSHA-approved Roof Control Plans obtained from the 30 deep cover coal mines NIOSH visited, together with underground observations and discussions with the staff at the mines.

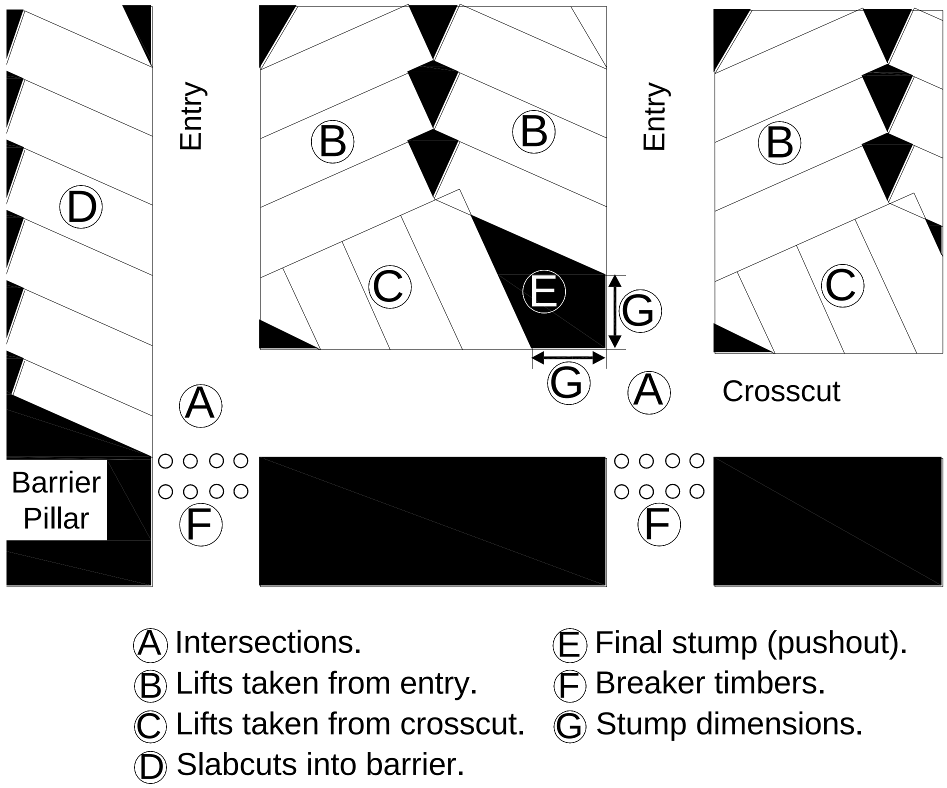

Figure 15. Pillar recovery, showing intersections, the final stump, and other details.

Figure 16. Photograph of Mobile Roof Supports deployed underground.

Engineered Final Stumps

The final pillar stump (sometimes called the "pushout") provides critical roof support during pillar recovery. Once it is removed, or is made too small to provide support, the active intersection may become unstable, like a chair with one leg removed. Prior to 1997, almost half of all fatal roof falls during pillar recovery occurred during or just after extraction of the final stump or last lift (Mark et al., 1997).

Traditionally, miners tried to extract all the coal during pillar recovery because they were concerned that stumps would inhibit caving and cause the outby pillars to squeeze. However, recent experience indicates that fears about leaving stumps were exaggerated. While fewer and fewer mines have recovered pushouts over the past few years, the incidence of squeezes has not noticeably increased.

In most cases, the optimum pillar extraction plan purposely leaves a final stump that has been engineered to provide roof support without inhibiting caving. Suggested guidelines for sizing the final stump, based on detailed rock mechanics analysis of pillar extraction experience, were presented by Mark and Zelanko in 2001. To help ensure that the actual stumps left underground are not accidently cut smaller than their designed size, Mark and Zelanko (2001) also recommended that the section foreman mark the stump dimensions on the rib with spray paint as a guide to the continuous miner operator.

The evaluation of the Roof Control Plans at the 30 deep cover mines studied found that, of the 28 mines using Christmas tree or left-right extraction sequences (figure 11) as their primary retreat method, only 5 currently extract the final pushout. At the others, an engineered stump, usually measuring 8 by 8 ft or 10 by 10 ft, is left as a roof support. Six of the mines do not take any lifts from the crosscut, thereby leaving a much larger final stump. The two mines that use outside lifts with continuous haulage do not leave a stump. Most of the Roof Control Plans also require that the final stump be clearly marked on the rib.

Mobile Roof Support (MRS)

Traditionally, timber posts provided supplemental support for pillar recovery, but setting posts on a pillar line is a very high-risk activity. MRSs are safer because they can be set remotely. MRSs also provide better ground control, and they decrease the potential for material handling injuries.

Most of the deep cover retreat mines have adopted MRS technology. Only 5 of the 30 mines in the survey still relied solely on timber for supplemental support during retreat mining. The other 25 mines normally employ four MRSs on each pillar section, although several of them do have plans that allow them to use two MRSs in conjunction with timbers, or even for retreat mining solely with posts. These additional plans generally incorporated other safety features as well, however, such as not extracting any lifts from the crosscut.

Enhanced Roof Bolt Support

In the past, one striking feature of the pillar recovery fatalities was that the victim was nearly always beneath bolted roof. In many cases, bolt failure was itself implicated in the fatality.

Sheared and broken 5/8-in, fully-grouted rebar bolts contributed to three of the four fatal roof fall incidents that have occurred in deep cover retreat mines.

NIOSH and MSHA have advocated using longer and/or stronger bolts to support areas that will be retreat mined. In addition, cable bolts or other special bolts are employed in intersections, which are the most hazardous locations for miners during pillar recovery. Thirteen of 25 fatal pillar recovery incidents since 1992 involved falls of the active intersection, and three more took place in intersections further from the mining activity.

Of the deep cover retreat mines surveyed, all but four routinely install extra supplemental support in the intersections where retreat mining is planned. The extra support typically consists of a pattern of 4 to 6 cable bolts or resin-assisted mechanical shell bolts, 8 to 12 ft long.

These three technologies seem to have had a significant impact on the safety of room-and-pillar retreat mining. However, there are a number of other procedures and technologies that could also be helpful, as discussed below.

Identification and Monitoring of Geologic Hazards

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. Eight of the 22 fatal pillar recovery incidents since 1992 occurred where the roof consisted of weak rocks such as shale, mudstone, claystone, or drawrock. Geologic discontinuities, such as slips, slickensides, horsebacks, joints, or hillseams, contributed to six more pillar line fatalities.

In more than one-third of the fatal incidents, poor conditions were observed in the area before the fatality occurred, but no action was taken. 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.

Conducting a geologic assessment of the entire panel before retreat mining commences is another 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, or other hazardous features. It is good practice to plan to skip some lifts in order to leave coal as support for such features. In extreme cases, such as where hillseams run down entries for long distances, it would be prudent to forego pillar recovery operations. Intersection spans should also be measured and additional support installed in any that are significantly wider than usual.

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 of MRSs 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.

Optimizing Cut Sequences and Mining Plans

When developing a mining plan for pillar recovery, mines should address a number of related questions to maximize safety, including:

- Will lifts be taken from the crosscut before they are taken from the entry?
- Will slab cuts into the barrier be taken from the intersection?
- Will two roadways for haulage be used when the final lifts are taken from the crosscut (in plans where the lifts from the crosscut are taken last)? Or should timbers or MRSs be used in the intersection to limit access to just one roadway?
- What are the best cut sequences if just two MRSs are employed?
- When is it helpful to leave fenders of coal between the lifts?
- Can cable bolts or other intrinsic supports provide protection equivalent to that obtained from breaker timbers?
- When should supplemental support be installed in the entry and/or crosscut, in addition to being installed in the intersection?

Another issue is the size of the stump when no lifts are taken from the crosscut. If the guidelines provided by Mark and Zelanko (2001) for typical stumps are used, the resulting stump is considerably stronger than the guidelines intended. In some circumstances this could inhibit caving or create the risk of an airblast. It might then be appropriate to move the last lift closer to the entry, if that would not compromise the stability of the intersection.

Work Procedures and Miner Positioning

Careful planning of the production process, good supervision, and training and retraining are essential to safe pillar recovery. Analysis of past fatalities shows that miners should only be present on the pillar line if they need to be there. Of the 26 victims of roof falls during pillar recovery since 1994, eight were not performing an essential production function when they were killed. Moreover, since 1994, there have been four multiple ground fall fatality incidents during pillar recovery, and *none* during any other activity. In eight other pillar recovery incidents, miners were injured by the same roof falls that killed their co-workers.

The victim in 38% of the fatalities since 1994 was the continuous miner operator or helper. According to MSHA's Program Policy Manual, "Investigation of a few of these [fatal roof fall accidents that occurred during pillar recovery operations] revealed that miners were occupying work locations inby the mining machine while coal was being mined or loaded. This practice should be discouraged, recognizing that recently mined coal pillars reduce the amount of support in these areas." With regard to 30 CFR 75.221, Roof Control Plan Information, the Policy Manual states that "work procedures and location of miners while coal is being mined or loaded should be incorporated into the Roof Control Plan as part of the description of the mining system utilized during pillar recovery."

Unfortunately, several of the victims in pillar recovery fatalities have been MRS operators that were standing unnecessarily in unsafe, inby locations. Best practices for using MRSs include:

- During all lifts, MRS units should be kept as close as practical to the continuous mining machine.
- Upon completion of mining in a given pillar, the units should be moved sequentially until they are between solid coal pillars.
- Personnel should remain at least 20 ft away from MRSs when they are being pressurized or depressurized.

Retreat mines should have plans in place for performing maintenance in safe locations, and for retrieving a disabled or stuck MRS. They should also have plans for safe retrieval of a continuous mining machine that becomes trapped in a roof fall.

Major Hazard Risk Assessment (MHRA)

Ideally, ground control safety during retreat mining could be best achieved with an ongoing risk management program that involves the entire workforce. One step in this direction being used extensively in other mining countries is MHRA (Iannacchione et al., 2008). As part of the deep cover study, NIOSH facilitated two trials of the MHRA approach at underground coal mines in southern West Virginia. Each mine created a risk assessment team that consisted of a range of employees in the retreat mining process, from engineers and mine managers to supervisors and face workers.

The teams first reviewed the pillar extraction mining system and identified associated hazards and threats to the operation. The hazards were ranked by their likelihood of occurrence and their consequence to safe operations of the mine. The teams then analyzed the greatest threats individually, and systematically identified potential unwanted events. The output from the process includes a priority list of existing controls for monitoring and auditing, and a second list of potential new controls. These controls consisted of:

- *Best practices*, such as measuring intersection dimensions to ensure that spans are within acceptable standards,
- *Enhanced communication*, such as providing foremen with an air horn to provide warnings to their crew,
- *Standard operating procedures (SOP*) to remove unnecessary personnel from high risk areas,
- *Protocols for emergency response actions*, such as using inflatable air bags to lift heavy rocks,
- *Efficient monitoring* using test holes and simple geotechnical instruments;
- *Audits* to ensure that all the controls are actually in place and the procedures are being followed.

Based on the trials at the two mines, NIOSH concluded that retreat mining operations could benefit from the MHRA approach. Low probability events, like those that the teams addressed, can have significant consequences if they do occur. Discussing all existing prevention controls and recovery measures helps to re-focus the operation, making sure that all the necessary systems are being applied. However, the trials also demonstrated the importance of subsequent monitoring and the auditing of the most important actions identified by the teams if the MHRA is to be truly successful.

Prevention of Rock Falls

Most rock fall injuries underground, more than 400 per year, are not caused by large roof falls, but rather by relatively small pieces of rock falling from between supports. Analysis of the MSHA accident and injury statistics from 2006 to 2008 shows that miners in deep cover retreat operations are not at significantly greater risk of rock fall injury than other room-and-pillar miners (table 2). One part of the explanation may be that roof bolt operators are often injured by falling rocks, but roof bolting is not a normal part of the retreat mining process when left-right or outside lift cut sequences are used.

Still, approximately 50 deep cover retreat miners are injured each year by rock falls. Wire mesh, or roof screen, has shown itself to be the most effective rock fall prevention technology (Robertson et al., 2003). Several highly productive non-retreat room-and-pillar mines in the Illinois Basin currently install roof screen on a regular basis (Compton et al., 2008), but screen is seldom used in central Appalachian mines.

Prevention of Rib Falls

Rib falls are a serious hazard at deep cover pillar recovery 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 (table 1). Rib falls have killed 18 mineworkers since 1994, including four at deep cover pillar recovery mines (though none of the incidents occurred during retreat mining operations). The most recent rib fall fatality occurred in August 2009 at a deep cover pillar retreat mine.

The two main factors that lead to an increased risk of rib falls are thicker coal seams and higher stress levels. For example, analysis of the 18 fatal rib fall incidents reveals that more than half occurred at depths exceeding 1,000 ft, and the mining height was at least 7 ft in every case.

Rib bolting can be highly effective in reducing the risk of rib falls. It is significant that rib bolts had apparently not been installed at any of the 18 U.S. fatality sites (Mark et al., 2009). When rib bolts are installed, it is normally in a pattern of 4- or 5-ft bolts spaced about 4 ft apart. Sometimes the bolts are angled to anchor in the roof, or the pattern is designed to support particular rock or coal layers. Mines that rib bolt often do not do it everywhere, but instead have criteria based on the seam height and/or the depth of cover. It also seems that rib bolting is seldom explicitly mentioned in a mine’s Roof Control Plan.

There are two main types of machines that are used to install roof and rib bolts. *Outside-control* machines are the traditional standard in thin to moderate height seams. However, these machines require that the operators place themselves between the machine and rib, where they are most exposed to unstable rib conditions. Moreover, some outside control machines are not equipped with rotating heads that can drill non-vertical holes. Unless these machines are fitted with special rib drills, they cannot be used to install rib bolts.

The other type of roof bolting machine is the inside-control, or walk-through. With these machines, the drill heads are between the operators and the ribs, providing a significant level of protection from rib falls. Although originally designed for thicker seams, walk through machines are now available with chassis heights as low as 36 inches.

Of the 30 deep cover pillar recovery mines for which data was available, five installed rib bolts and used walk-through machines during the period 2006-2008. None of these five mines experienced more than one rib fall injury during those three years. During the same time frame, 21 deep cover mines did not support the ribs and used outside control roof bolting machines. At twelve of these mines, two or more miners were injured by rib falls. It seems clear that rib bolting and walk-through roof bolters can be very effective in reducing the risk of rib falls.

Prevention of Pillar Failures

The Crandall Canyon disaster was an unfortunate reminder of the importance of pillar design to mine safety. The MSHA report on the disaster (Gates et al., 2008) concluded that "it was obvious, at the most fundamental level, that the accidents at Crandall Canyon Mine were precipitated by pillar failures….The South Barrier [pillar] was the last substantial block of coal supporting the mountain and, as it was removed, the mountain was simply too heavy for the remaining pillars."

Pillars normally provide *global stability* to a mine by carrying the weight of hundreds, or even thousands, of feet of rock. Artificial supports, like roof bolts or posts, provide *local stability* to the roof directly above the miners. But even the strongest man-made support—an MRS for example—can only carry several tens of feet of rock. Without global stability, no local support strategy can hope to be effective.

When the pillar design is inadequate, three types of failures can occur:

- *Squeezes*, which are non-violent events that may take hours, days, or even weeks to develop. Squeezes are the most common type of pillar failure, and they commonly cause roof instability, floor heave, and rib falls. Because they develop slowly, however, the affected area is usually abandoned before there are any injuries to miners.
- *Collapses*, which occur when a large number of overloaded pillars fail almost simultaneously, usually resulting in a destructive airblast. Most collapses in the U.S. have occurred under low cover (less than 500 ft), and they have been associated with the slender pillar remnants that have been left in worked-out gob areas after partial pillar recovery operations. The prevention of collapses was the subject of much research during the early 1990s, and shallow-cover collapses have been very rare during the past decade.
- *Bursts*, which can affect just a small portion of a single pillar, or may destroy many pillars at once. Bursts have many causes, and not all of them can be eliminated by pillar design. As will be shown below, however, the likelihood of large bursts can be greatly reduced when properly sized pillars are used.

Accordingly, pillar design is a fundamental mining science, with roots that go back more than a century (Mark, 2006). There are three basic steps in almost every pillar design methodology:

- Estimate the applied loads, including any abutment loads;
- Estimate the strength of the coal pillars;
- Compare the load to the strength, and employ engineering criteria to determine whether the design is adequate.

Today, mine planners use two main types of pillar design methodologies. *Empirical methods* use relatively simple heuristics to estimate the pillar strengths and loads. Despite their simplicity, they can be extremely powerful when they are calibrated against large databases of real-world mining case histories. *Numerical models*, on the other hand, try to replicate the actual behavior of the rock mass. They typically require accurate and detailed rock properties, as well as calibration against underground measurements or observations.

Following the Crandall Canyon disaster, MSHA distributed a series of Program Information Bulletins (PIBs) and other documents that describe 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). The documents define “complex and/or non-typical roof control plans” as where “room-and-pillar retreat mining is conducted at depths of 1,000 ft or greater” (Stricklin, 2008). Other criteria that meet the definition of “complex and non-typical” Roof Control Plans include:

- Any pillar design that does not meet the NIOSH recommended stability factors calculated using the ARMPS computer program;
- Mines that have a history of bursts, regardless of the depth of cover;
- Unusual circumstances, such as retreat mining between two gob areas or mining in areas of high stress created by a multiple seam interaction.

MSHA further stated that all “complex and non-typical” Roof Control Plans will be subject to “extensive” review and analysis, usually involving MSHA’s Technical Support Roof Control Division (Stricklin, 2008).

NIOSH believes that the above MSHA documents have been successful in placing pillar design practice in U.S. underground coal mines on a solid engineering foundation. Their consistent application will significantly reduce the risk of pillar failure and its attendant hazards to coal miners. The next sections of this report will discuss specific pillar design methods in the context of the MSHA documents.

Analysis of Retreat Mining Pillar Stability (ARMPS)

ARMPS is the most widely used pillar design method in the U.S. It is an empirical method that was originally developed by NIOSH in the mid 1990s (Mark and Chase, 1997). Statistical analysis is used to derive design guidelines that separate the “successful” case histories (those where the entire panel was mined without pillar failure) from those that are “unsuccessful.” The goal is to reduce the risk of the most hazardous types of pillar failures—collapses and bursts—to a minimum. A low level of residual risk is tolerable for pillar squeezes, because they are significantly less hazardous than bursts or collapses. NIOSH analysis shows that during the past 25 years there has not been a single fatality associated with a pillar squeeze.

The original 1997 ARMPS database consisted of approximately 150 case histories, representing a broad range of cover depths. The analysis indicated that when the depth of cover was less than 650 ft, a Stability Factor (SF)[36] of about 1.5 was a reasonable starting point. However, for deep cover cases, two conclusions were drawn:

- Many panels with an SF well below 1.5 were successful, and
- No single SF was able to separate the successful from the unsuccessful cases.

Accordingly, a follow-up study was conducted which focused on deep cover pillar recovery (Chase et al., 2002). During this study, an additional 100 case histories were collected from mines in central Appalachia and the West where the depth of cover exceeded 750 ft. The analysis indicated that squeezes were the most likely failure mode when the depth of cover was less than 1,250 ft, but bursts predominated in the deeper cover cases.

The findings of the 2002 study were summarized as design guidelines (table 3). The two key conclusions were that:

- The suggested ARMPS SF for production pillars declined as the depth of cover increased, from 1.5 at 650 ft of cover to 0.8 at 1,250 ft of cover;
- Barrier pillars were extremely important to the success of pillar design for retreat mining, particularly in burst-prone ground.

Figure 17 shows the recommended guidelines, together with the 2002 deep cover case history database.

Table 3. Recommended ARMPS Stability Factors (Chase et al., 2002).

	Depth (H)	**Weak and Intermediate Strength Roof**	**Strong Roof**
ARMPS SF (Production pillars)	H<650 ft	1.5	1.5
	650 ft ≤ H ≤ 1,250 ft	1.5 - [H-650] / 1000	1.4 - [H-650] / 1000
	1,250 ft ≤ H ≤ 2,000 ft	0.9	0.8
Barrier Pillar SF	H > 1,000 ft	≥ 2.0	≥ 1.5* (≥ 2.0**)
	H<1,000 ft	No Recommendation	

*Non-burst-prone ground
**Burst-prone ground

[36] The Stability Factor in ARMPS is the total load bearing capacity of the pillars on the pillar line (or "Active Mining Zone" (AMZ)) divided by the total load applied to those pillars.

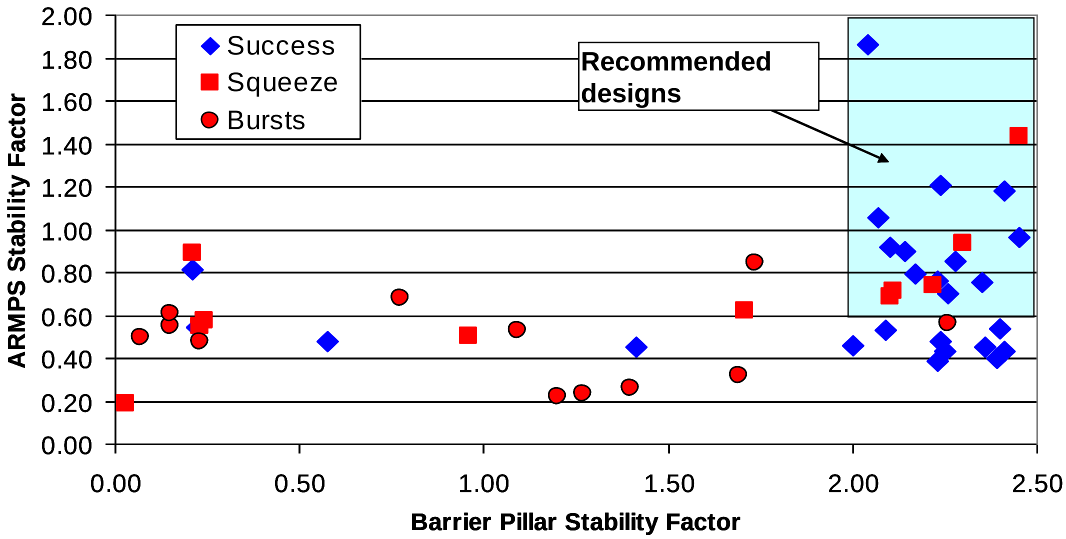

Figure 17. The 2002 ARMPS deep cover ARMPS database, showing the recommended design guidelines, including the recommended barrier pillar SF (after Chase et al., 2002.)

Unfortunately, the ARMPS pillar design recommendations were not followed at the Crandall Canyon Mine. The MSHA report (Gates et al., 2008) concluded that ARMPS "was inappropriately applied" and that the contractor who developed the design "recommended a pillar design for the South Barrier section that had a lower calculated pillar stability factor than recommended by the NIOSH criteria." In addition, the contractor "did not consider the ARMPS barrier pillar stability factors[37] in any of their analyses."

After the Crandall Canyon disaster, MSHA "strongly encouraged" mine operators to make use of the ARMPS program. MSHA PIB No. P08-8 specifically called mine operators' attention to the NIOSH recommended design criteria as defined in table 3. The PIB also emphasized the NIOSH recommendation that ARMPS barrier pillar stability factors be considered when the depth of cover exceeded 1,000 ft (Stricklin and Skiles, 2008), and that recovering pillars between two worked-out gob areas should be avoided.

During the current study, more than 200 new retreat mining case histories were added to the ARMPS database from the information gathered during the deep cover mine visits. Some additional case histories were obtained from the NIOSH multiple seam case history database (Mark et al., 2007). Finally, any multi-pillar burst case histories that were not already in the database were added.[38]

[37] The Barrier Pillar SF in ARMPS is the estimated total load bearing capacity of the portion of the barrier pillar adjacent to the AMZ, divided by the total load applied to that portion of the barrier pillar.
[38] The final ARMPS database includes 695 case histories from 127 different coal mines. The cases are from 42 counties in 10 states, covering all the U.S. coalfields. A total of 67 different coal seams are represented. About 90 cases, or 13% of the total, are from Utah and Colorado. There are 130 "unsuccessful" case histories in the database, including 25 bursts. The ARMPS database includes multi-pillar and single pillar burst case histories where there is sufficient information to calculate an ARMPS SF. Case histories that involve a multi-seam interaction are not included in the ARMPS database.

The new database was evaluated using the existing pillar loading model and deep cover ARMPS design criteria. As shown in figure 18, the results were very similar to those obtained by Chase et al. in 2002 with the smaller database[39]. The analysis confirms that ARMPS continues to apply a high level of protection against pillar failure. To demonstrate, as was discussed earlier, the pillar designs did not meet the NIOSH ARMPS criteria in every one of the 12 multi-pillar bursts that have occurred during retreat mining in the past quarter-century.

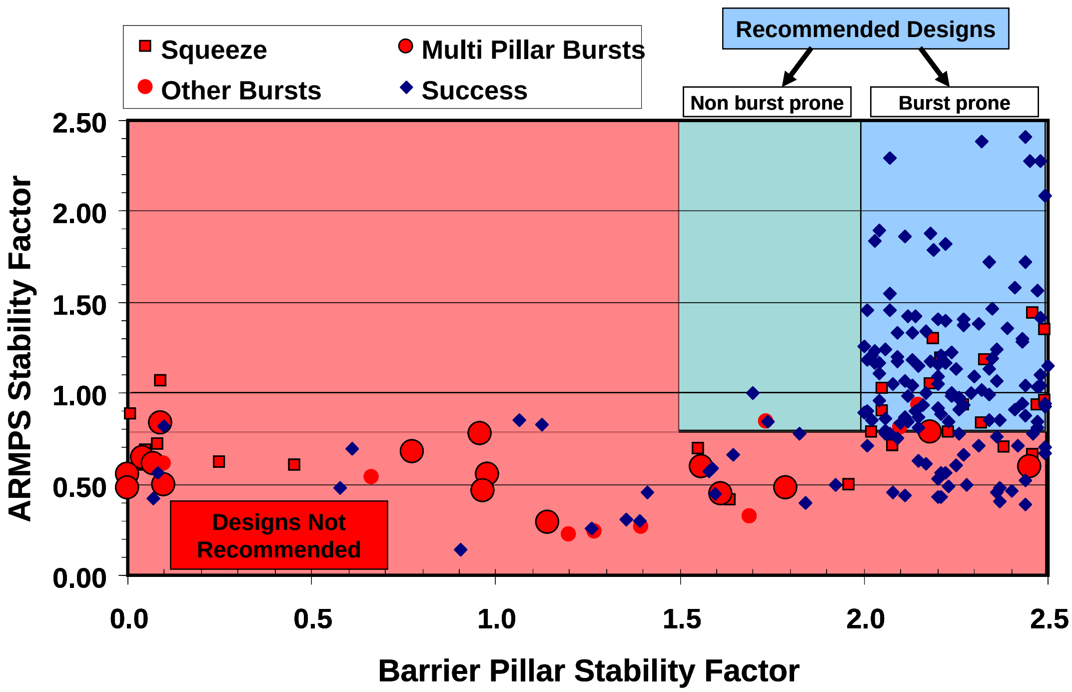

Figure 18. The deep cover case histories in the updated ARMPS database, showing the 2002 recommended guidelines for stability factors for production and barrier pillars.

During the study, NIOSH also identified several potential improvements to the ARMPS program. In particular, two types of numerical models were used in conjunction with statistical analysis of the case history database to evaluate the method that ARMPS uses to distribute the overburden loads. Currently, ARMPS employs the "tributary area theory," which assumes that every pillar always carries the load of the rock directly above itself (plus its share of any abutment loads from mined-out areas). Under deep cover, however, the barrier pillars may carry more than their share of the load because they are stiffer than the production pillars (figure 19). The numerical models indicate that this "pressure arch" effect may transfer as much as 30% of the load to the barriers.[40]

[39] In order to present the data more clearly, a graphical technique called "jittering" has been used to create this plot. There are a number of cases where the barrier pillar stability factor is equal to zero (i.e., no barrier was used). So that these points do not plot on top of one another, they were randomly assigned a barrier pillar SF between 0 and 0.2. Similarly, for the cases where the barrier pillars were very large, stability factors between 2.0 and 2.5 were randomly assigned.

[40] It would be extremely difficult to confirm pressure arch behavior underground with actual stress measurements, because of the large volumes of rock involved.

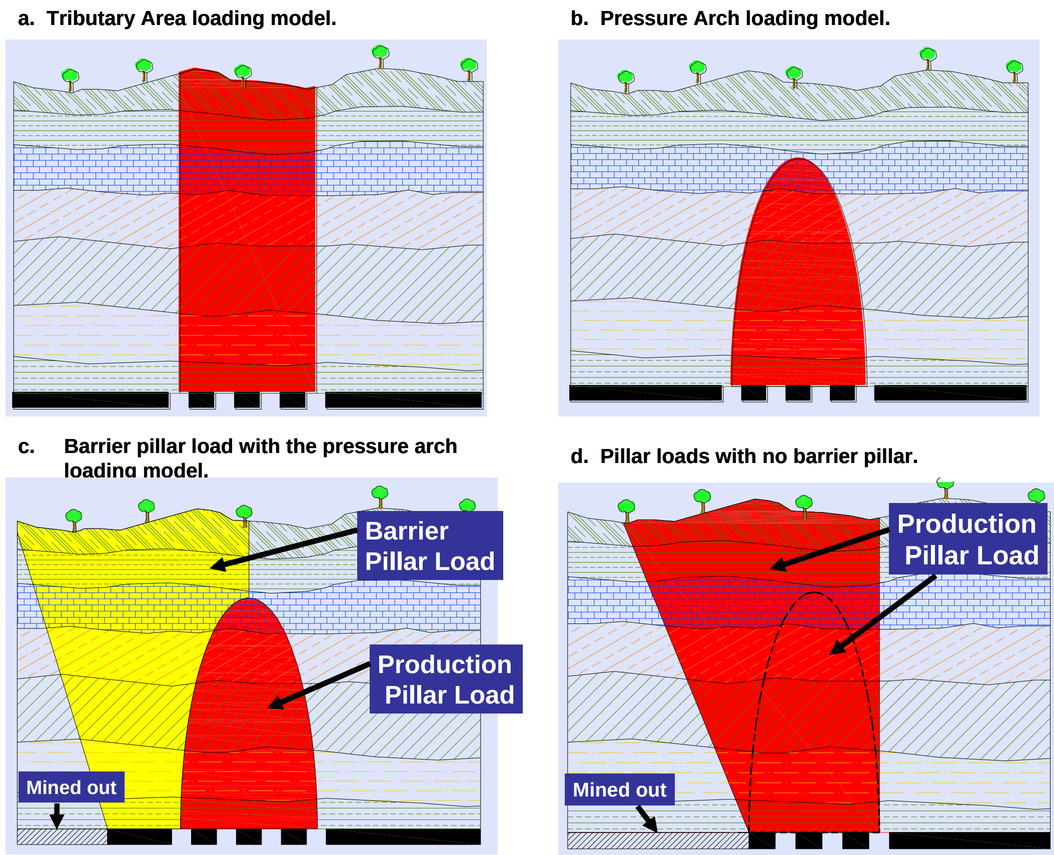

Figure 19. ARMPS loading models.

To accommodate a pressure arch loading model, a new version of ARMPS is being prepared. Analysis shows that the pressure arch model achieves approximately the same overall discrimination between successful and unsuccessful case histories as the 2002 version (figure 20).[41] However, the pressure arch model is still preferable to the more complicated 2002 criteria, because:

- It provides an improved margin of safety against large-scale, multi-pillar burst events.
- The inherently greater stability of narrow panels is recognized, because the pressure arch model transfers proportionately more load from narrow panels to the barrier pillars.
- A single ARMPS SF criterion (SF=1.5) can be employed across the entire range of cover depths.
- Barrier pillars and the production pillars can employ the same design criterion of SF=1.5.

The pressure arch loading model should further improve the reliability of the ARMPS program.

[41] The reason for the similarity is that the depth-dependent production pillar stability factor criteria used by the 2002 criteria (see table 3) is a de-facto pressure arch model that is mathematically nearly equivalent to the explicit 2010 model.

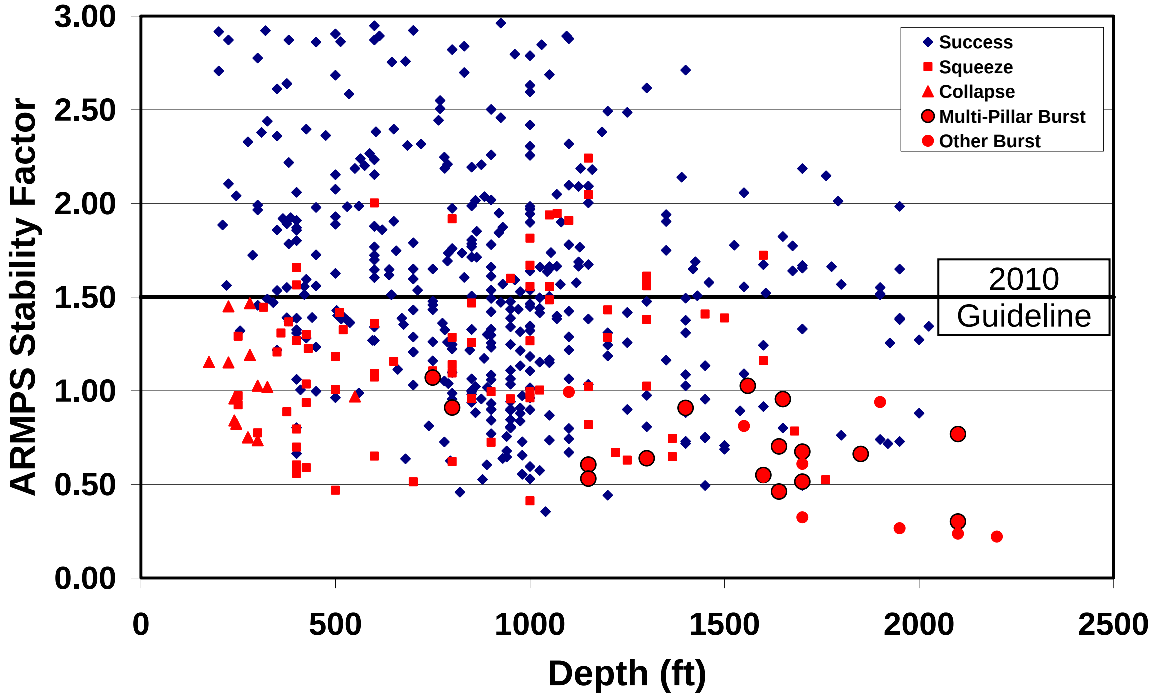

Figure 20. The updated ARMPS database, showing the new SF recommended guideline.

Analysis of Multiple Seam Stability (AMSS)

Coal has been mined in the central Appalachian coalfields for more than a century, and one consequence is that nearly every remaining underground reserve has been impacted by past mining activity. The mountains of the central Appalachian coalfields are honeycombed with worked-out mines. Nearly every active deep cover retreat mining operation is working on a property where coal has been extracted in the past, from seams either above, below, or both. Many coal mines in the West, including one of the two deep cover pillar retreat mines, are also in multiple seam situations. Fortunately, multiple seam interactions are usually associated with particular remnant structures[42] in the previously worked-out mine, and so they only occur in particular locations that can often be identified in advance.

Multiple seam interactions can cause pillar failure, roof falls, rib instability, and floor heave. In some cases, they can be so severe and hazardous that mining is impossible in that location. In other cases, it may be possible to develop pillars but not recover them. In many cases, however, the interaction may be barely noticeable.

To assist mine planners in evaluating the hazards of multiple seam interactions, NIOSH developed another empirical design method called AMSS (Mark et al., 2007). To build the

[42] Most multiple seam interactions are caused by "remnant structures," like barrier pillars, that were left next to fully extracted gob areas in the previously mined seam. The remnant structures are carrying concentrated abutment loads, which can be transferred through the intervening overburden to the active seam. For more details, see Mark et al., 2007.

AMSS database, NIOSH collected more than 300 multiple seam case histories from 40 mines, including twelve deep cover pillar recovery mines. These data were analyzed with the multivariate statistical technique of logistic regression.

NIOSH found that many of the failed multiple seam cases involved pillars whose stability factors appeared inadequate once the additional multiple seam stresses were considered. Therefore, the first step in the AMSS procedure is to evaluate the pillar design. The AMSS computer program calculates the single seam ARMPS SF, and then it automatically runs a simple numerical model that provides the additional multiple seam stress. If the final, multiple seam stability factors appears inadequate, it can be improved by increasing the pillar width, dropping crosscuts, or reducing the entry width.

Many other multiple seam interactions occurred even where the pillar SF was adequate. The intensity of these interactions was found to depend upon the type of remnant structure in the previous seam, whether that previous seam was above or below the active mine,[43] and the strength of the roof in the active mine. The extra stresses created by multiple seam interactions are also known to create a higher risk of coal bursts.

AMSS gives mine planners a tool that they can use to evaluate multiple seam situations that cannot be addressed by a single seam ARMPS analysis. If a more detailed analysis is desired, or if the geometry is too complicated for AMSS, a numerical model may be an appropriate choice.

LaModel

The LaModel program is a numerical model that is used to estimate the stresses and displacements in thin tabular deposits like coal seams. It belongs to a family of boundary element, "displacement discontinuity" programs that have evolved from algorithms originally developed by Salamon in the 1960s. They are widely used for pillar design because they can conduct pseudo-three-dimensional analyses of large areas of coal mines quickly and efficiently. LaModel is unique in that it includes "laminations," allowing it to more accurately simulate the behavior of layered, sedimentary overburden. Compared with ARMPS, its primary advantages are that it can be used in more complicated mining geometries, and it accounts for such factors as multiple seam interactions and variable surface topography.

LaModel has a long history of successful application at coal mines throughout the world. However, like any numerical model, its results are highly dependent on the material properties and other input parameters used in the analysis. In addition, the results need to be checked against real-world measurements, observations, and past experience to ensure their accuracy.

LaModel was the primary design tool used to design the pillars used at Crandall Canyon. However, the MSHA report concluded that the LaModel analysis used in the design was "flawed" in that it:

[43] Active mines that are *above* previous full-extraction workings are more prone to multiple seam interactions, because the strata have already subsided and may have been fractured in the process.

- Used an area for back-analysis that was inaccessible and could not be verified for known ground conditions, which resulted in an unreliable calibration and the selection of inappropriate model parameters.
- Modeled the pillars with cores that would never fail regardless of the applied load, which was not consistent with realistic mining conditions. The indestructible nature of the modeled pillars was not considered in the interpretation of the results.
- Underestimated the modeled abutment stresses, which were inconsistent with observed ground behavior and previous studies at Crandall Canyon and nearby mines.

One clear lesson of the disaster was that mine planners need more guidance in calibrating and interpreting LaModel simulations. As part of the current project, WVU developed standardized procedures for calibrating LaModel, and checked them against more than 40 detailed deep cover case histories provided by NIOSH. Each case history included an AutoCad mine map and information regarding the actual conditions in the mine. Three analyses were performed on each case history:

- An ARMPS analysis,
- An "idealized" LaModel analysis, which employed simplified geometry and overburden to match the ARMPS model, and
- A full LaModel analysis with the actual pillar plan resulting from the mining process and surface topography.

The result is that by using these guidelines, a mine planner can begin a calibrated LaModel analysis with a baseline model that is closely linked to ARMPS and its comprehensive case history database. Subsequently, more complex models that build upon the baseline should then remain tethered to past experience in their most critical components.

Other Pillar Design Methods for Retreat Mining

A variety of other pillar design methods have been employed to size coal pillars, including other numerical methods, analytical methods, and local experience. In 2009, MSHA released a Program Information Bulletin (PIB) addressing the use of numerical modeling for ground control modeling (Skiles and Stricklin, 2009). The PIB states that "it cannot be over-emphasized, that in order to be of value, a numerical model must be validated and provide a realistic representation of the underground environment for which it is applied." The guidelines in the PIB address, among other things, techniques for using *systematic* underground observations to verify a model's accuracy. Such verification is particularly important for finite-element and finite-difference models whose "calculation capabilities have outstripped our ability to obtain the accurate, in situ input parameters which are critically important to realistically modeling the true mechanical response and failure of geologic material" (Heasley, 2008).

Verification is also critical for analytical methods and methods based on local experience. Such methods potentially have the advantage of considering, directly or indirectly, site-specific factors that may not be considered in ARMPS. And, as figure 21 shows, there is still a considerable amount of variability in pillar design performance that ARMPS currently cannot explain. Thus, it is critical that local methods only be applied where they have a long and proven track record. Applying them to a new seam, a new mine, or even a different geologic environment at the same mine should not be done without comprehensive engineering analysis. Moreover, much like LaModel, local methods should always be compared to a benchmark ARMPS analysis, and major discrepancies should be thoroughly investigated before a design is implemented.

Education and Training

The "inappropriate application" of ARMPS and the "flawed" LaModel analysis that resulted in the failed pillar design at Crandall Canyon underscore the need for a sound understanding of pillar design throughout the mine planning community. For years, ARMPS and LaModel have been described in professional papers, they have been included in the curricula of mining engineering programs at major universities, and they have been the subject of numerous NIOSH training sessions and workshops, yet a flawed design was still implemented at Crandall Canyon.

Shortly after the disaster, NIOSH and MSHA developed guidelines for the use of the ARMPS program. Most of these were already contained in "help" and "resource" files included with the program. However, now they were added to the ARMPS program to help users avoid the pitfalls that might result in an inappropriate application. These guidelines were also discussed in an MSHA PIB distributed to the industry (Stricklin and Skiles, 2008).

Such guidelines are valuable, but they are no substitute for real understanding of the software and its application. Therefore, an important component of the current project is to prepare training manuals based on standardized "best practices" for both ARMPS and LaModel. The training manuals will discuss the technical basis for the programs, and they will provide step-by-step directions, along with practical considerations for developing pillar designs. The manuals will also document a number of complete analyses of case histories that illustrate the potential difficulties and complications that can be encountered. The new manuals, together with new versions of the software, will be the focus of a major NIOSH training initiative during 2010.

Unfortunately, such efforts are insufficient to address another fundamental underlying issue that was exposed by the Crandall Canyon disaster. Compared with global standards, the U.S. coal industry suffers from a dearth of expertise in ground control and other mining specialties. In Australia, for example, nearly every large underground mine employs a full-time ground control specialist who assesses and manages all the ground control risks faced by the operation. The U.S. industry, despite its larger size, employs only a handful of ground control specialists in any capacity. Ground control usually falls upon a non-specialist mining engineer as one responsibility among many others. Improvement over the long-term will require the universities to produce ground control specialists, perhaps through continuing education programs, with the required practical and theoretical knowledge. More importantly, it will also require the mining companies to employ more specialists who can use their expertise to reduce risk and improve mine safety.

Prevention of Coal Mine Bursts

Although coal bursts are not common events in U.S. coal mines, over the years a number of prevention controls have been proposed and tried. These include techniques for assessing the risk, specialized mine designs and mining sequences, and work practices that minimize exposure to bursts. Remediation controls focus on de-stressing the ground and managing the caving process, and there are a variety of techniques for monitoring the burst hazard. Other burst prevention and monitoring techniques have been employed internationally. Not all of these techniques have been equally successful, nor are they equally suited to the specific needs of today's deep cover retreat mining operations.

Pre-Mining Burst Risk Assessment ("Red Zones")

The first step in burst control is to identify those "red zone" areas that might be prone to bursts. As was stated earlier, the two key factors associated with a high likelihood of bursts are high stress and strong roof geology. Although the science is still imperfect, these two factors can be quantified and combined with local experience and other factors to identify zones of higher burst risk.

The German "Rockburst Prevention System" focuses on geologic criteria (Baltz and Hucke, 2008). By comparing rock cores from 35 areas that experienced bursts with 400 from areas that did not, Baltz and Hucke found that the burst risk was significant when there was:

- A 15-ft-thick "package" of strong sandstone in the first 30 ft above the mining horizon, or
- A 6-ft-thick "package" of strong sandstone within the first 15 ft of the floor.

The competence of a sandstone package is assessed using a rock mass classification system that is similar to the Coal Mine Roof Rating system (see footnote 27). A risk of bursts is also assumed to be present when mining crosses remnant structures in previously mined seams. On the other hand, areas above or below previously mined-out gob areas are assumed to be stress relieved and not prone to bursting. Numerical models have been employed to assist in assessing the stress conditions since the 1970s.

Using these criteria, zones of "potential risk for rock burst" are outlined. Even though just one German mine has actually had a burst during the past 10 years, almost every one has some zones of potential risk that receive special treatment.

One U.S. mine, in Harlan County, KY, also defines "red zones" using both depth and geologic criteria (figure 21), as follows:

- A massive sandstone at least 5 ft thick is found within 4.25 ft above the coal seam, and
- The depth of cover exceeds 1,550 ft.

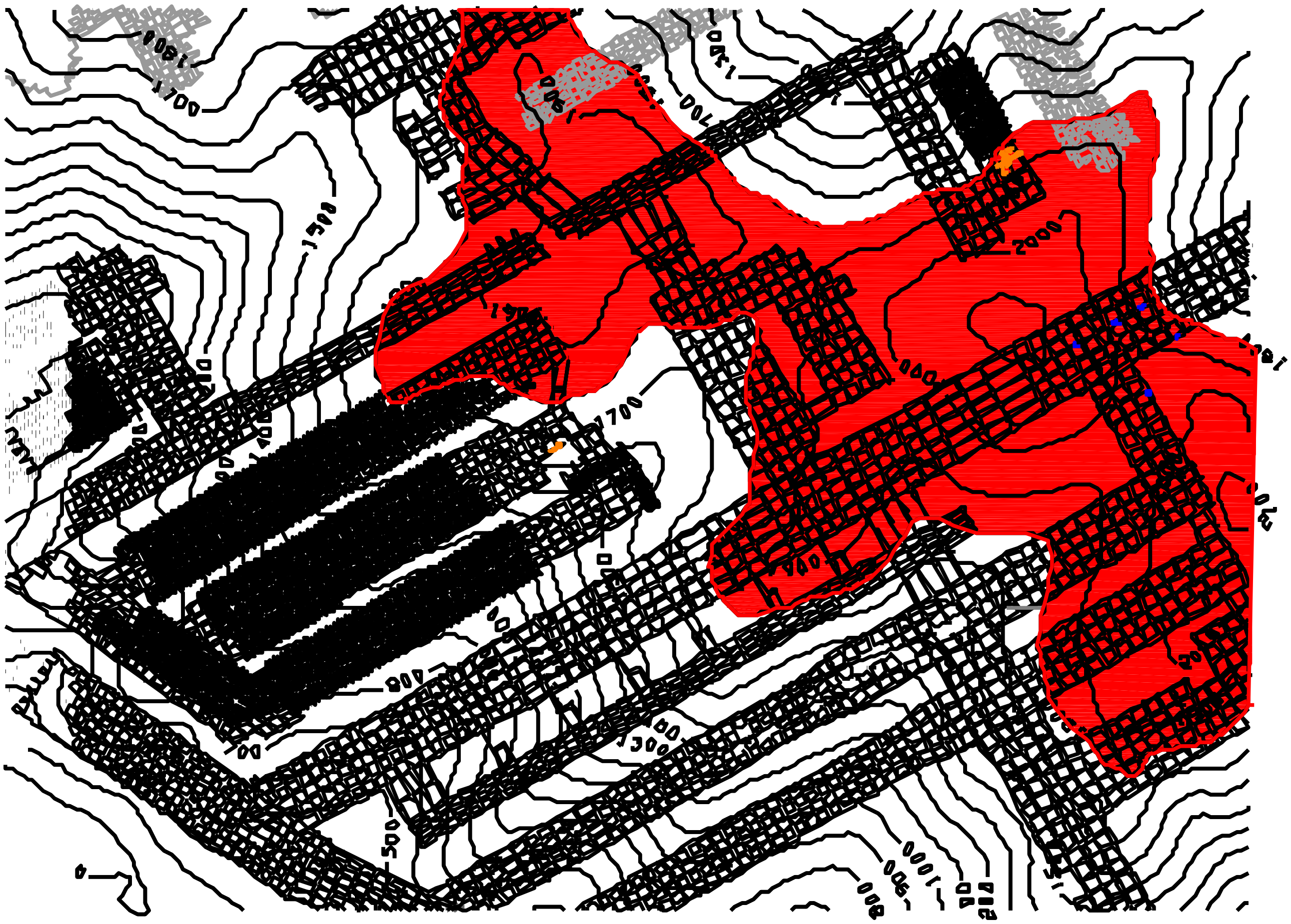

Figure 21. A "red zone" defined by the depth of cover at a U.S. retreat mine.

As in the German system, areas beneath gob areas in an overlying seam are considered to be de-stressed, and not liable to bursting.

Other geologic factors that have been identified as contributing to a heightened burst risk include:

- Faults (Holland, 1958; Holub, 1997; Agapito and Goodrich, 2000; Alber et al., 2008; Swanson et al., 2008)
- Rapid changes in the depth of cover (Holland, 1958; Maleki 1995, Maleki et al., 1999)
- Sandstone channels that concentrate load (Agapito and Goodrich, 2000; Hoelle, 2008)
- Seam rolls (Iannacchione and Zelanko, 1995)

Once an area has been developed, the opportunities for geologic characterization are greatly expanded. Where pre-mining surface boreholes are typically spaced thousands of feet apart, test holes can be drilled underground hundreds or even tens of feet apart. This is particularly important when bursts are associated with features, such as sandstone channels, that may be just several hundred ft wide, as was the case at an eastern Kentucky longwall mine (Hoelle, 2008).

Underground test holes are already included in most mine Roof Control Plans, but they are typically not much deeper than the roof bolts. To determine the location and thickness of strong roof rocks for burst risk evaluation, test holes will usually need to be at least 10 ft long. The drillers should be trained to look for sandstone, and the results should be recorded and plotted on a map. The Kentucky room-and-pillar mine mentioned earlier uses test holes to refine the boundaries of the "red zones" used in its mine planning.

Test holes are more valuable if they are supplemented by occasional underground core holes. Samples obtained from coring can be rated for competence, and tested for strength and stiffness. Because they can be drilled off-cycle, they should not have any impact on production. Underground core holes were used extensively at the burst-prone longwall mentioned above (Hoelle, 2008).

The "Stability Mapping System" described by Wang and Heasley (2005) appears to be an excellent platform for combining all of these factors into a mine-specific burst risk rating. The system utilizes the popular AutoCAD/SurvCADD platform to enable inputting of geologic data such as rock strengths, layer thicknesses, faults, rolls, etc. The mapping system is also integrated with the LaModel software which can provide overburden stress, multiple seam stress, and mining-induced abutment stresses. Each of the individual factors can be weighted to generate an overall stability index map for the entire property.

Mine Design for Burst Control

Once "red zone" areas at elevated risk of bursts have been identified, the next step is to determine what steps to take to minimize the risk within them. According to the hierarchy of risk reduction effectiveness (Iannacchione et al., 2008), the most effective way to reduce risk is to eliminate it entirely. In the context of burst control, this would be achieved by not mining at all in the areas of greatest risk.

Where complete avoidance is not deemed to be necessary or practical, mining within "red zones" should be limited to development only. For example, main entries could be developed under the deepest cover, with the production panels located where the cover was lighter. It is also possible to take advantage of the flexibility of the room-and-pillar mining system by leaving a few rows of pillars in place in the areas of greatest risk.

For room-and-pillar mines with relatively small "red zones" of high risk, avoidance techniques are practical because they are inexpensive, cause little disruption to the mining process, and are highly effective. If a property has extensive reserves under deep cover, however, it might make sense to employ longwall mining instead of room-and-pillar mining, as the burst-prone Colorado mine discussed earlier chose to do.

Any time retreat mining is going to be conducted under deep cover, pillar design is the primary engineering control. Barrier pillars that largely isolate each new panel from the abutment loads arising from previously mined ones are particularly effective. The NIOSH burst database shows that nearly all multi-pillar bursts during the past quarter century have occurred where the barrier pillars were either inadequate or not used at all. This finding is consistent with that of Holland (1958), who found that over 80% of the 163 bursts he analyzed had occurred on "pillar points," which are created when barrier pillars are either completely extracted or not used in the first place.[44]

As the MSHA report noted, the West Mains area of the Crandall Canyon Mine had been "primed for a catastrophic pillar failure because the mine design created a large area of equally sized and marginally stable pillars" (Gates et al., 2008). Had substantial barrier pillars been used to compartmentalize this large area, and to isolate it from the adjacent longwall gob areas, a mine collapse of the magnitude of the one that occurred would have been highly unlikely if not physically impossible. In the future, the consistent application of properly sized barrier pillars between retreat mining panels should go a long way towards reducing the risk of bursts in deep cover room-and-pillar mines.

Burst Control Cut Sequences

Another set of engineering controls are special cut sequences that have been used to reduce the burst risk during the pillar recovery process. The basic principle that they all share is that they try to avoid, as much as possible, extracting highly stressed coal.

For example, "bump cuts" have been used as an alternative to the hazardous practice of splitting pillars on the pillar line. The bump cuts are made while the pillars are still one or even two rows outby the pillar line, so that only thin fenders are recovered next to the previously extracted gob area. The Olga Mine in West Virginia developed the most sophisticated bump cut plan during the early 1980s, as illustrated in figure 22 (Iannacchione and Tadolini, 2008). The technique was judged to be successful in controlling bursts, but because it required mining operations to be conducted in three rows of pillars simultaneously, it was difficult to implement. A deep cover retreat mine that attempted to employ a bump cut plan in the early 2000s quickly concluded that it was "not productive or economic," and instead opted not to retreat mine in the areas of deepest cover (Newman, 2008).

Several other cut sequences, like the "thin pillar" method, have been proposed for reducing the burst risk while extracting barrier pillars (Iannacchione and Tadolini, 2008). While such techniques undoubtedly represented an improvement on earlier methods, they still required development in abutment zones and they created pillar points[45]. Since barrier pillars are normally left in place today, such methods would likely only find application in reducing the size of exceptionally wide barriers.

[44] Holland (1958) also recommended that development should not be conducted on a pillar line, another objective that is attained when barrier pillars are left in place.

[45] A "pillar point" is created when a pillar is adjacent to extensive mined-out gob areas on two sides. Pillar points have long been associated with increased risk of bursts (Holland, 1958). The use of barrier pillars precludes the creation of pillar points.

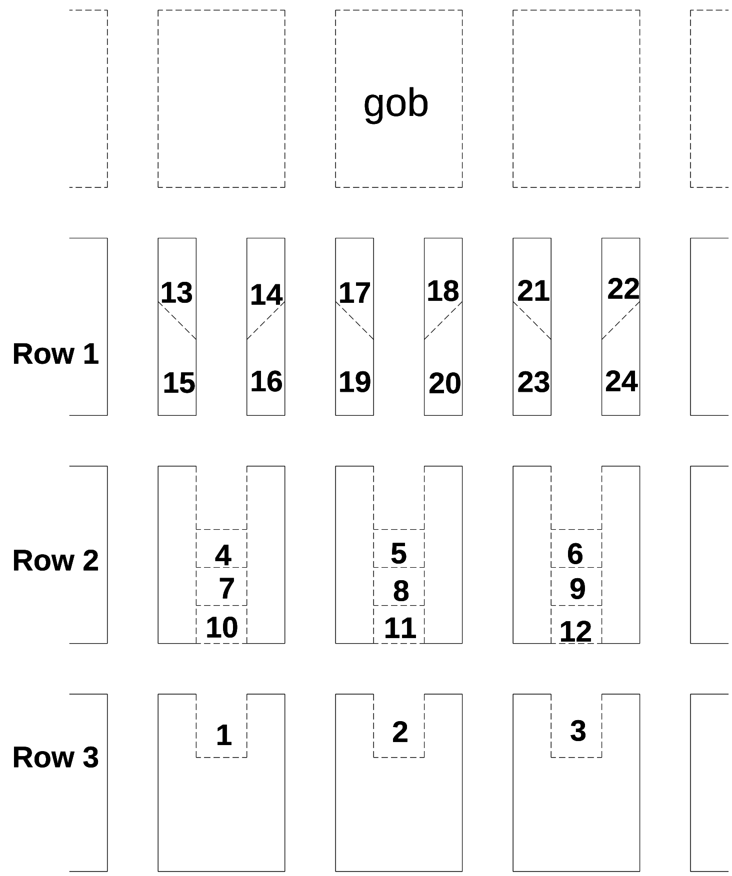

Figure 22. "Bump cut" sequence used at the Olga Mine in early 1980's.

One simple technique that can be implemented easily is narrow cuts. By taking lifts that are just one-half the width of the continuous miner cutting head, the risk of extracting highly stressed coal is reduced, and the remaining pillar is given more time to yield and redistribute its load.

In conclusion, it does not seem that any burst control cut sequence is capable of reducing the risk of bursts within an identified "red zone" to an acceptable level. These sequences are therefore not a reliable alternative to the avoidance strategies described in the previous section.

Administrative Procedures and Personal Protective Equipment

One reason that coal bursts are particularly dangerous during retreat mining is that it is very difficult to remove all personnel from the hazardous area. In contrast to longwall mining, where it is possible to use automation to limit exposure, during retreat mining the continuous miner operator and the hauler operator must be near where the coal is being cut and loaded. The controls that are available to reduce the exposure of personnel to the burst hazard include:

- Allowing only the minimum number of persons required to extract the coal into the areas where coal is being mined.
- Providing some kind of passive protection for remote-control equipment operators.

- Positioning remote-control equipment operators as far from the active mining as practical.
- Providing miners with personal protective gear, such as helmets and face shields.

While such measures may be helpful for mitigating the effects of smaller events, they are of little to no value in larger ones. Moreover, whatever value they have is compromised if they are not consistently employed. Therefore, they require worker training and constant management attention. Overall, these controls could be considered in deep cover areas where there may be some very low level of bump risk, but they do not provide nearly enough protection to allow pillar recovery within an identified "red zone."

Monitoring Techniques

The pre-mining burst risk assessment only provides a starting point for hazard management. Monitoring conducted during the mining process can also provide an ongoing update of the risk.

Observations During Mining: In deep cover areas, crew members can be trained to make regular observations of features that have been associated with elevated risk, including the following (Varley and Whyatt, 2008):

- Lagging caves,
- Unusual spalling from the ribs, or lack thereof;
- Red dust at the coal-to-roof or coal-to-floor interface (signifying frictional failure of highly stressed coal).

By far, the most valuable indication that the burst risk is increasing is an increase in the number or intensity of small, non-injury bursts (near misses). These should be carefully recorded even if they are not reportable to MSHA by the criteria established in CFR 50.2. It is also critical that management systems be in place to analyze and respond to these observations.

Rock mechanics instrumentation, such as convergence, pillar stress, or support load measurements, have sometimes been used to monitor conditions in burst-prone areas. However, no accepted criteria for interpreting such measurements in terms of burst risk have ever been developed.

Probe Drilling: The closer to the pillar edge a highly stressed zone of coal is, the greater the risk that mining will produce a burst. Probe drilling is used to determine the location of the highly stressed coal. Small (typically 2-in diameter) auger holes are drilled into the pillar or longwall face, and the cuttings are measured as they are removed from the hole. If the coal is yielded and de-stressed, the volume of the cuttings will nearly equal the volume of the hole. If highly stressed coal is encountered, however, the volume of cuttings will greatly exceed the theoretical volume of the hole. In addition, various dynamic effects, such as audible knocking and jamming of the drill rod, may be encountered (Haramy et al., 1995).

In German mines, probe hole drilling is considered to be the *only* reliable technique for establishing when a *recognized* (as opposed to a *potential)* risk of rock burst is present (Baltz and Hucke, 2008). Specific criteria are established for evaluating the results from each hole, as well as for the distance between holes and the amount of mining that can take place before probe drilling must be conducted again. Typically, the drilling is conducted once per day, and then the face is advanced no more than 15 ft or so. If high stress is encountered too close to the face, then de-stressing operations must be conducted before mining can continue.

During the 1980s, probe hole drilling was conducted at a handful of eastern room-and-pillar mines and western longwalls. While generally successful, the technique was considered too time consuming for routine use in the U.S.

Seismic Tomography: Seismic tomography is an indirect technique that could eventually be used in place of probe hole drilling to identify the location of high stress zones in coal pillars. The technique creates an image, similar to an MRI, of the variation of the seismic velocity within the pillar. High velocity zones are interpreted as being highly stressed, while low velocities indicate low stress or yielded zones. Unfortunately, "a simple direct process to integrate the acquisition and analysis of tomographic data into the daily operations of a mine has not been developed," and so the technique must be considered an "immature tool" (Westman and Luxbacher, 2008).

Seismic Monitoring: Monitoring of mining-induced seismicity (MIS) is very common in deep, hard rock mines. The metal mining industries of South Africa, Canada, and Australia have the most severe rockburst problems, and they are probably the most advanced in terms of integrating seismic monitoring into their rockburst hazard management systems.

Seismic monitoring systems in these countries have a number of different goals:

- *Rapid response*: Immediate determination of the location and magnitude of a seismic event allows a mine to decide whether mine workings are likely to have been damaged, to dispatch rescue workers to the correct location if necessary, and to shut down and inspect critical machinery or infrastructure which may have been damaged (such as the mine shaft).
- *Back-analysis* of large, damaging events: Seismic data is helpful, after the fact, in understanding the cause of seismic events. This is particularly the case where damage has made access impossible.
- *Hazard assessment*: A statistical evaluation of small-scale seismicity within a given volume of rock can often give an indication, at an early stage, of the relative likelihood of a large event occurring.
- *Mine design validation*: Seismic monitoring is used to characterize the rock mass response for comparison against model predictions.

The deep gold mines in South Africa use seismic monitoring as a key part of their long-term (years) and medium-term (months) seismic hazard analysis. Short-term, (hours to days), hazard analysis, in contrast, is not yet reliable. In these mines, it is typical for seismic hazard maps to be made available on a daily basis. Furthermore, seismic monitoring information is used at weekly safety meetings and monthly planning meetings, where mine panel layouts are modified to reduce hazardous seismic activity. Despite these efforts, mining-induced seismicity accidents still occur. Moreover, the in-mine seismic systems are complex and maintenance-intensive, and they require trained personnel to analyze and interpret the data.

Seismic monitoring in coal mines is much less common, but is done routinely in burst-prone longwall mines in Poland, the Czech Republic, Russia, and Germany. In Germany, however, seismic monitoring is primarily focused on the effects of mining-induced seismicity on surface structures. Day-to-day assessments of the burst hazard underground are instead based almost exclusively on the results of probe drilling.

<u>U.S. Practice</u>: During the past decade, there has been only one in-mine micro-seismic system installed inside a U.S. coal mine, at Utah's Willow Creek longwall mine, where NIOSH temporarily operated a system in 1999-2000. NIOSH is not aware of any seismic monitoring that has ever been conducted in a room-and-pillar coal mine anywhere in the world, other than as part of a small U.S. Bureau of Mines research study nearly 25 years ago (Condon and Munson, 1987).

All current monitoring systems in the US employ arrays of geophones installed on the surface. In the Utah coalfields, seismic monitoring is conducted by the University of Utah's seismic network (UUSS). The focus of the UUSS recent studies has been to determine where and when MIS occurs, although there have been a few studies of source properties and mechanisms of MIS. The data collected by system is available to the public through the UUSS website.

Beginning in 2005, two of three longwall coal mines in western Colorado cooperatively joined with NIOSH to fund and develop a seismic network with specific performance goals relating to mining. These are to:

- Characterize mining-related and naturally occurring seismic activity,
- Implement a real-time event monitoring and notification tool, and
- Collect data for use in research studies addressing dynamic failure hazards.

Raw and processed data are available only to the system users through a password protected internet web page. Time-critical information is also distributed via email and pager notifications.

The seismographic coverage is very sparse in the central Appalachian coalfields. Regional networks, such as the one operated by Virginia Tech in Blacksburg, VA, have served in a primarily confirmatory role for only the very largest mining-related seismic events. One eastern mine has recently installed a seismic monitoring system above its active longwall, but the data is proprietary.

<u>Operational Considerations</u>: It is not possible to develop a generic set of rules for seismic hazard assessment that would be applicable to all mines. Rockbursts have various immediate causes. Rockburst processes involve structures of different size scales, ranging from individual pillars to widespread geologic units in the overburden or underburden. As a result, seismic monitoring systems for hazard assessment are custom designed for the specific situation with consideration given to mine depth and layout.

A seismic hazard management system that incorporates seismic monitoring begins with the actual seismic acquisition hardware and processing system. The capability of a seismic system can be described by its sensitivity, its accuracy in locating events, and its processing speed. Both sensitivity and accuracy are improved by having more sensors, and keeping them close to the mining front.

The next consideration is the interpretation process. The processing begins with the determination of the locations and magnitudes of seismic events. The events can be clustered into groups sharing the same causative features, and each cluster analyzed independently to see if patterns emerge.

It is important to assess the seismic data in conjunction with other geotechnical and geological information. For this purpose, a seismicity knowledge database should be assembled, containing such information as rock types and properties, geological structures, stress measurements, observations of ground conditions, production rates, and numerical modeling results.

A set of procedures also needs to be set up for using the seismic information, in conjunction with geological and geotechnical data, to produce the desired risk assessments. It is also important to identify the set of actions that the mine will take in response to different levels of seismicity. Possibly the most important aspect of a seismic hazard management plan is the performance of periodic critical reviews. Understanding ground conditions requires an iterative process of formulating models, gathering data, and testing and refining the models.

Coal Burst Remediation Techniques

Remediation techniques are used to lower the burst risk by reducing the stress, changing the characteristics of the coal or roof, or inducing caving. The goal is to address the residual hazard that has been primarily controlled by mine design.

De-stressing

The principle behind de-stressing is simple: Highly stressed coal is intentionally made to fail. Once the coal has failed it cannot burst, and the load it formerly carried is transferred elsewhere. De-stressing is typically the next step after probe drilling has identified a hazardous high-stress zone near the rib. There are three main techniques used for de-stressing:

> *Auger drilling* is the technique of choice in German mines. The holes used there are typically 4-6 in in diameter. Like the probe holes, when the de-stress holes encounter highly stressed coal they remove a volume of cuttings that is much greater than the theoretical hole volume. According to Bräuner (1994), the drilling causes a number of small rock bursts in the hole until the stresses are no longer high enough to cause further bursting. The drills must be operated remotely because of the high risk of a burst being triggered by the drilling operation.
>
> *De-stress blasting*, or volley firing, uses small explosive charges to soften the coal in place. The technique reduces the likelihood of prematurely triggering a burst because only small diameter holes are drilled to set the explosives.

Hydrofracturing is thought to work by fracturing the coal in much the same way as de-stress drilling. It is attractive because it uses small drill holes that are less likely to trigger a burst, and it does not require the use of explosives.

Water infusion at low pressure may soften the coal by increasing its moisture content, but German experience indicates that to be effective infusion must be conducted weeks or months ahead of mining.

Starting in the 1950s, several U.S. mines experimented with de-stressing with mixed results (Varley and Whyatt, 2008; Haramy et al., 1995). De-stress drilling trials were generally considered unsuccessful, in some cases because they triggered hazardous bursts, and in others because they did not adequately relieve the high stress. De-stress blasting and drilling are both extremely time consuming and costly in terms of lost production. Hydrofracturing, on the other hand, has been helpful at several operations (Hoelle, 2008; Varley and Whyatt, 2008). It was employed as recently as 2006 to de-stress longwall chain pillars in advance of mining (Buchbaum, 2006).

NIOSH did not find any evidence that de-stressing has ever been employed successfully in a room-and-pillar retreat mine, however. In a longwall mine, de-stressing has the effect of moving the load deeper into the longwall panel where it is safely confined. In a room-and-pillar mine, the load would most likely transfer to another pillar, with possibly unpredictable results. Moreover, de-stressing techniques are generally not meant to be used everywhere, but instead only where dangerous high stresses are known to be present. Without a reliable and practical method for locating high stresses in the coal seam, the value of de-stressing techniques is greatly reduced.

Caving Control

Roof that does not cave, or "hangs up" above the worked-out area, has been associated with an elevated risk of bursts. The hanging roof adds to the load carried by the pillars on the pillar line, and it also creates the possibility of a "shock burst" when it finally does fracture. The sudden collapse of large areas of roof can also cause a hazardous airblast.

Artificial caving has been induced by explosives, such as the "torpedo" blasting used in the upper Silesian coalfields of Poland and the Czech Republic, or by hydraulic fracturing (Varley and Whyatt, 2008). At Moonee Colliery, in Australia, one or two holes drilled from underground and pressurized for about one hour were sufficient to hydrofracture a massive, 100-ft-thick conglomerate roof. The regular application of this relatively simple process was credited with saving the mine by preventing the hazardous airblasts that had previously been caused by irregular and infrequent caving (Hayes, 2000). Understanding the stress environment within the roof was critical to the design of the hydrofracture treatment (Mills et al., 2000).

Findings and Recommendations

Findings - Conditions under Which Retreat Mining is Used

- The most significant hazards faced by deep cover retreat miners are:
  - Ground falls, including large "roof falls," smaller "rock falls" that occur between roof supports, and "rib falls" that come from the side walls of the mine.
  - Pillar failures that can affect large areas of a mine, but are usually non-violent "squeezes" that occur slowly and seldom result in injuries to mine workers.
  - Coal bursts, which are violent seismic events that cause coal to be ejected into the mine with enough energy to injure or kill miners.

- Approximately 10% of the underground coal mined in the U.S. came from retreat mining, mainly from the central Appalachian coalfields of southern West Virginia, Virginia, and eastern Kentucky. There are approximately 39,000 underground coal miners in the U.S., and about 900 of them work in the deepest mines that have recovered pillars at depths greater than 1,500 ft. An additional 2,200 retreat miners work at depths between 1,000 and 1,500 ft. Only one of the current deep cover pillar recovery mines has ever worked at depths exceeding 2,000 ft.

- There are approximately 42 deep-cover mines in the U.S., and 40 of them are located in the central Appalachian coalfields. The other two are located in Utah and Colorado.

- Nearly all the deep cover retreat mines use a "left-right" pillar extraction cut sequence.

- The roof and floor rocks in the Western and Central Appalachian coalfields are generally stronger than those found in other U.S. coalfields. Coal seam strength, on the other hand, is very difficult to measure, but does not seem to vary significantly from region to region. The seam thickness at 87% of the mines NIOSH visited during the current study was between 5 and 8 ft.

- 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.

- In recent times bursts have been rare events in retreat mines. There have been no bursts in room-and-pillar mines since the events at Crandall Canyon in 2007, and only two room-and-pillar mines in operation today have ever experienced a burst.

- High stress is a universal feature of burst-prone conditions. That is why the incidence of bursting increases as the depth of cover increases. Strong, massive sandstone is also usually found near the seam where bursts have occurred.

- When all other factors are the same, room-and-pillar retreat mining is more burst-prone than longwall mining.

- The practice of pillar splitting, which requires mining into the highly stressed pillar core, has historically been associated with a disproportionate number of burst incidents.

- Most mining-induced seismicity is generated in the overburden as it caves and subsides. Only a tiny fraction of mining-induced seismic events are associated with coal bursts.

- The most dangerous bursts are those, like the one at Crandall Canyon, that result in extensive damage to at least several pillars. Seventeen of these multi-pillar events have occurred during the past 25 years. Most of these can be attributed to inadequate pillar design. However, two room-and-pillar mines have experienced non-injury multi-pillar bursts that would have been difficult to link to the pillar design.

Findings - Prevention of Ground Falls

- There has been just one fatal roof fall on a pillar line in the past 4 years, compared with an average of two per year during the previous decade.

- The three key technologies for improving the safety during retreat mining are: (1) leaving an engineered final stump, (2) using Mobile Roof Supports, and (3) using longer and stronger roof bolts, particularly in intersections. Of the deep cover mines studied, 82% are leaving an engineered final stump, 83% are using MRSs, and 87% routinely install extra supplemental support in the intersections.

- Best practices for retreat mining safety include:
    - Conducting a geologic assessment of the entire panel before retreat mining commences.
    - Conducting pre-shift and on-shift examinations that include thorough assessments of geologic conditions.
    - Measuring intersection spans and installing additional support in any that are significantly wider than usual.
    - Using test holes to determine if there is roof separation and monitoring them during mining to see if conditions worsen.
    - Monitoring the pressures and loading rates of MRSs to provide information on roof stability.

- Roof Control Plans for retreat mining should incorporate work procedures, including the location of miners while coal is being mined or loaded.

- Best practices for using MRSs include:
    - During all lifts, MRS units should be kept as close as practical to the continuous mining machine.
    - Upon completion of mining in a given pillar, the units should be moved sequentially until they are between solid coal pillars.
    - Personnel should remain at least 20 ft away from MRSs when they are being pressurized or depressurized.

- Retreat mines should have plans in place for performing maintenance in safe locations, for retrieving a disabled or stuck MRS, and for safe retrieval of a continuous miner that becomes trapped in a roof fall.

- Retreat mines are still in need of guidance regarding the best ways to address the following issues in their Roof Control Plans:
    - Whether lifts can be taken from the crosscut before they are taken from the entry?
    - Whether slab cuts into the barrier should be taken from the intersection?
    - Whether two roadways should be used for haulage when the final lifts are taken from the crosscut (in plans where the lifts from the crosscut are taken last), or whether timbers or MRSs should be used in the intersection to limit access to just one roadway?
    - Which cut sequences provide the most stability if just two MRSs are employed.
    - Under what circumstances leaving coal fenders between the lifts improves stability?
    - Whether cable bolts or other intrinsic supports can provide protection equivalent to that obtained from breaker timbers?
    - Under what circumstances supplemental support should be installed in the entry and/or crosscut in addition to being installed in the intersection?
    - What is the appropriate size of the final stump to be left if no lifts are taken from the crosscut?

- The technique of MHRA has demonstrated its potential to help mining operations lessen the risk of deep cover pillar recovery, but only if they follow through by implementing, monitoring, and auditing the control measures that are identified during the MHRA process.

- Miners in deep cover retreat operations are not at significantly greater risk of rock fall injury than other room-and-pillar miners, although approximately 50 deep cover retreat miners are injured each year by rocks falling from between or around supports.

- Wire mesh, or roof screen, is the most effective rock fall prevention technology.

- Miners in deep cover retreat operations are approximately three times as likely as other room-and-pillar miners to be injured in a rib fall.

- The two main factors that lead to an increased risk of rib falls are thicker coal seams and higher stress levels. There have been 18 fatal rib fall incidents in U.S. coal mines since 1994, with more than half occurring at depths exceeding 1,000 ft. The mining height was also at least 7 ft in every case.

- Rib bolting can be highly effective in reducing the risk of rib falls. Outside-control roof bolting machines require that the operators place themselves between the machine and rib, where they are most exposed to unstable rib conditions. Inside-control (walk-through) roof bolting machines provide a significant level of protection from rib falls. Data from 30 deep cover pillar recovery mines shows that mines that installed rib bolts and used walk-through machines had significantly lower rib fall accident rates than mines that did not use this technology.

Findings - Prevention of Pillar Failures

- "At the most fundamental level, the accidents at Crandall Canyon Mine were precipitated by pillar failures" (MSHA report on the Crandall Canyon disaster).

- Pillars normally provide *global stability* to a mine by carrying the weight of hundreds, or even thousands, of feet of overburden rock.

- When the pillar design is inadequate, three types of failures can occur:
    - *Squeezes*, which are non-violent events and are the most common type of pillar failure;
    - *Collapses*, which occur when a large number of overloaded pillars fail almost simultaneously, usually resulting in a destructive airblast; and,
    - *Bursts*, which can affect just a small portion of a single pillar or may destroy many pillars at once.

- Following the Crandall Canyon disaster, MSHA distributed a series of guidance documents to the mining industry which define the pillar design best practices that mine operators should follow when preparing their Roof Control Plans. The widespread implementation of these best practices has greatly reduced the risk of pillar failures.

- The NIOSH Analysis of Retreat Mining Pillar Stability (ARMPS) program is the most widely used pillar design method in U.S. ARMPS is an empirical pillar design method that has been successful because it has been calibrated against a large database of case histories.

- In 2002, NIOSH published ARMPS pillar design recommendations for deep cover retreat mining that included recommended stability factors for production pillars and barrier pillars. Unfortunately, these recommendations were not followed at the Crandall Canyon Mine. During the current study, more than 200 new retreat mining case histories were added to the ARMPS database. Statistical analysis confirmed that ARMPS continues to apply a high level of protection against pillar failure. With these new case histories, NIOSH is developing an updated version of ARMPS that will incorporate several new features, including a "pressure arch" loading model.

- Nearly every active deep cover retreat mine operating today is working on a property where multiple seam interactions may be encountered. To assist mine planners in evaluating the hazards of multiple seam interactions, NIOSH developed another empirical design method called Analysis of Multiple Seam Stability (AMSS).

- The LaModel program utilizes a numerical model that has a long history of successful application at coal mines throughout the world. Like any numerical model, its results are highly dependent on the material properties and other input parameters.

- Under NIOSH contract, researchers at WVU developed standardized procedures for conducting calibrated analyses that are closely linked to ARMPS and its comprehensive case history database. These improvements are being implemented in a new version of the LaModel program.

- Other pillar design methods have been successfully employed, but it is essential that they be thoroughly validated for the underground environments for which they are applied.

- One of the lessons of the Crandall Canyon disaster was that mine planners need to understand both the theory and practice of pillar design. NIOSH and WVU are preparing training manuals for both ARMPS and LaModel that will be the focus of a major NIOSH education initiative during 2010.

- Compared with global standards, the U.S. coal industry suffers from a dearth of expertise in ground control and other mining specialties. Improvement will require a cultural shift in which the universities produce, and the mining companies employ, more specialists that can apply their expertise to reduce risk and improve mine safety.

Findings - Prevention of Coal Mine Bursts

- To help prevent coal mine bursts, “red zones” of significantly elevated burst likelihood can be identified based on the depth of cover, geologic factors that have been associated with past bursts, the potential for multiple seam interactions, and recent ground control experience. Other geologic factors that may contribute to a heightened burst risk include faults, rapid changes in the depth of cover, sandstone channels, and seam rolls. Underground test holes, supplemented by underground core holes, can be used to locate strong, thick roof rocks that can increase the risk of bursting. The “Stability Mapping System” described by Wang and Heasley (2005) appears to be an excellent platform for combining all of these factors into a mine-specific burst risk rating.

- Once “red zone” areas at elevated risk of bursts have been identified, the risk can be reduced by limiting mining within the “red zone” area.

- Pillar design is the primary burst prevention control any time that retreat mining is going to be conducted under deep cover. Panel widths should be limited and barrier pillars should be used to isolate each new panel from previously mined ones.

- Special “burst control” pillar extraction cut sequences have been used in the past, but none is likely to reduce the risk of bursts to an acceptable level within a "red zone."

- Administrative procedures, such as personnel positioning, passive protection, training, and personal protective gear, are of little value in protecting miners from the effects of large bursts. The most valuable indication that the burst risk is increasing is an increase in the number or intensity of small, non-injury bursts (near misses). These should be carefully recorded even if they are not reportable to MSHA by the criteria established in 30 CFR 50.2.

- Probe drilling to identify highly stressed coal is the *only* technique that German mines use to establish if mining can be conducted safely within a “red zone” of potential burst risk. Probe drilling is too time-consuming for routine use in modern U.S. mines.

- Deep, hard rock mines throughout the world routinely employ seismic monitoring in their rockburst hazard management systems. Seismic monitoring in coal mines is much less common, but is done routinely in burst-prone longwall mines in some European countries.

- Under NIOSH contract, the U of Utah convened a panel of international experts to evaluate the potential applicability of seismic monitoring to U.S. coal mines. The panel confirmed that no seismic monitoring system can *predict* a specific hazardous seismic event in advance. However, the panel felt that seismic monitoring could help improve the understanding of the causes of seismicity at a mine and could help provide a means of long- to medium-term seismic hazard assessment.

- In-mine seismic monitoring systems are complex and maintenance-intensive, and they require trained personnel to analyze and interpret the data. It is important to assess the seismic data in conjunction with other geotechnical and geological information.

- Remediation techniques are used to lower the burst risk by reducing the stress, changing the characteristics of the coal or roof, or inducing caving. NIOSH did not find any evidence that de-stressing has ever been employed successfully in a room-and-pillar retreat mine.

- NIOSH concluded that, within an identified “red zone,” no combination of currently available mining sequences, administrative procedures, or monitoring techniques can be relied upon to reduce the risk posed by coal bursts to an acceptable level.

Recommendations to Enhance the Safety of Retreat Mining

Burst Hazard Assessment: Although bursts are currently rare events in room-and-pillar mines, it is essential that mine operators identify areas of higher burst likelihood in advance of mining. NIOSH recommends that deep cover room-and-pillar retreat coal mines conduct regular burst hazard assessments for any areas where retreat mining is proposed and the depth of cover exceeds 1,000 ft. The assessments will identify “red zones” of significantly elevated burst likelihood based on the depth of cover, the geological conditions, the potential for multiple seam interactions, and recent ground control experience. The assessments should be guided by an experienced ground control professional, and should be conducted on at least an annual basis. The assessments could also include rock mechanics testing, underground observations and measurements, numerical modeling, and seismic monitoring.

Minimizing Burst Risk: NIOSH concludes that, within an identified zone of significantly elevated burst likelihood, no combination of currently available mining sequences, administrative procedures, or monitoring techniques can be relied upon to reduce the risk posed by coal bursts to an acceptable level. NIOSH therefore recommends that retreat mining should not be conducted within identified "red zones" of significantly elevated burst likelihood. Additional specific recommendations to limit the risk of violent coal bursts during retreat mining operations are as follows:

- At depths exceeding 1,000 ft, retreat mining should not be conducted without properly designed barrier pillars.
- At depths exceeding 1,000 ft, pillar splitting should not be conducted on the pillar line.
- At depths exceeding 2,000 ft, pillar recovery should not be conducted.

Pillar Design: Pillar design, including the use of properly sized barrier pillars, is the most effective technique for minimizing the risks of pillar failure and coal bursts under deep cover. NIOSH believes that the current MSHA guidelines regarding the technical and engineering data related to pillar design that mine operators must submit as part of their Roof Control Plans have been successful in placing pillar design practice in U.S. underground coal mines on a solid engineering foundation. The consistent application of these guidelines will significantly reduce the risk of pillar failure and its attendant hazards to coal miners.

Minimizing Roof Fall Risk: The greatest hazard to coal miners engaged in pillar recovery continues to be roof falls. During the past decade, significant progress has been made in developing technology to reduce the roof fall risk. However, this technology has not been uniformly applied. NIOSH recommends that a Pillar Recovery Partnership, consisting of representatives from NIOSH, MSHA, state regulatory agencies, coal operators, and labor, should evaluate the state-of-the-art in pillar recovery. The partnership will address:

- Cut sequences, stump sizes, and roof support for retreat mining;
- Mining methods for mine-specific conditions, such as twin-seam mining or areas where Mobile Roof Supports are inoperable;
- Training requirements and personnel positioning; and,
- Guidelines for when an incident involving a mining machine that is trapped by a roof fall should be reported to MSHA.

The ultimate goal of the Partnership will be to develop a handbook that mine operators can use to prepare MSHA-Approved Roof Control Plans for retreat mining.[46]

Research Recommendations

Determination of Criteria for High Risk or Red Zones

Although "red zones" of significantly elevated bump risk can be identified using current knowledge and experience, research should be conducted to improve the science and develop enhanced guidelines for defining "red zones." The research should focus on geologic and stress criteria and should consider U.S. and international experience.

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[46] This incorporates a recommendation from MSHRAC that "There is a need for the development of a best practices guide on how to safely do retreat mining with an emphasis on training. This needs to include the application of technology, proper mine designs, and operational considerations to ensure miner safety. The engineering plan has to incorporate the best practices considerations and provide detailed plans for mining of the coal pillars during the retreat operation" (MSHRAC minutes, January 2008).

Determination of Criteria and Reporting Requirements for Coal Bursts
Guidelines should be developed to provide a more specific definition of a coal burst and criteria for when coal bursts should be reported to MSHA.

Determination of Best Practices for Rib Support
Research should be conducted to reduce the number of injuries and fatalities associated with rib falls. A particular focus should be deep cover, thick seam, room-and-pillar mines that account for a disproportionately high percentage of rib fall injuries. The research should address both rib support and the proper use of roof bolting machines where the risk of rib falls is elevated.

Determination of Major Hazard Risk Assessment Techniques for Retreat Coal Mining
Research should be conducted to tailor Major Hazard Risk Assessment (MHRA) techniques to the specific needs of retreat coal mines and to transfer the technology to these mines. The effort should focus on helping mines follow through with the monitoring and audits that are necessary to the success of the MHRA technique.

Further the Understanding of Pillar Loading and Behavior for Deep Cover Mining
To continue to enhance the accuracy of the models used to design for deep cover conditions, basic research should be conducted into pressure arch behavior and the mechanics of squat coal pillars. The research should be based on field studies and involve stress measurements, and it should address the effect of roof, floor, and parting strength on burst-prone pillar behavior.[47]

Further the Understanding of the Application of Seismic Monitoring for Hazard Assessment and Rock Mass Behavior
Further seismic monitoring research conducted at demonstration sites where the technology and interpretation techniques can be tested and refined to advance the state of practice of seismic monitoring for hazard assessment in deep underground coal mines could enhance mine safety. Working technology and demonstrated benefits will reassure mines, and other stakeholders, that seismic monitoring is providing the maximum potential safety benefits.[48]

Assess the Current Conditions and the Future Application of Ground Control Specialists for Improved Safety of Mining Operations
Mine safety could benefit from a greater application of specialized ground control expertise to mine planning and operations. Development of a cadre of ground control specialists would require collaboration between universities, who would provide the relevant specialized training, and the mining industry, which would provide employment. Additional assessments could include:

[47]This incorporates a recommendation from MSHRAC that "An expansion of the research program is warranted, and there should be consideration given to conducting basic studies, including expanding field studies, to advance the understanding of the fundamental mechanisms of bumps and related types of failures. This expansion of research would complement the empirical studies" (MSHRAC minutes, January 2008).
[48] This incorporates a recommendation from MSHRAC that "Monitoring approaches should be considered as the research program advances, and particular topics mentioned by the Committee included seismic monitoring in collaboration with stress measurements. This is of interest as it relates to coal bumps and other types of dynamic failures" (MSHRAC Minutes, January 2008).

- The potential contribution of ground control specialists to mine safety at the level of the mine, the corporation, and the industry.
- The number of specialists currently engaged in the industry, and their responsibilities;
- The potential number of specialists that the industry could employ.
- The ability of current graduate programs to provide the appropriate theoretical and practical training.
- Recommended changes to graduate program curricula and delivery.

NIOSH recommends that the assessment be conducted by either the National Academy of Sciences or the Society for Mining, Metallurgy, and Exploration.

NIOSH Actions

To continue to ensure that the mining community has access to the best available pillar design technology, as well as the training to use it properly, NIOSH will undertake the following actions within existing resources:

1. Enhanced versions of ARMPS and LaModel will be completed this year and made available for distribution to the mining community via the NIOSH website.

    - A NIOSH Information Circular describing the new software and containing a number of worked-out, practical example problems will be published and distributed to the mining community.
    - NIOSH will develop a training initiative in pillar design, focusing on hands-on computer training with the ARMPS and LaModel software. The initiative will be aimed at both industry and regulatory personnel, and will feature Open Industry Briefings and short courses in a variety of coalfield locations.

2. NIOSH will investigate the development of a handbook that mine operators can use to prepare MSHA-Approved Roof Control Plans for retreat mining. Representatives from NIOSH, MSHA, state regulatory agencies, coal operators, and labor will be invited to participate, perhaps through a partnership effort, to compile state-of-the-art pillar recovery practices.

3. NIOSH will conduct research to improve the science and develop enhanced guidelines for defining "red zones" of significantly elevated bump risk. The research will focus on geologic and stress criteria and will consider U.S. and international experience.

4. NIOSH will define a research effort to reduce the number of injuries and fatalities associated with rib falls. The research will include the deep cover, thick seam, room-and-pillar mines that account for a disproportionately high percentage of rib fall injuries. The research will develop guidelines for rib support and for the proper use of roof bolting machines where the risk of rib falls is elevated, and will be initiated after the other NIOSH actions are completed.

5. NIOSH may conduct limited seismic monitoring research and encourage others to advance the state of practice of seismic monitoring for hazard assessment in deep underground coal mines. The primary focus of such research would be deep cover longwall mines and the goal would be to develop guidelines for:

   - Selecting the appropriate seismic acquisition hardware and processing system;
   - Interpreting the data, including the integration of geological, geotechnical, and mining information with the seismic data; and,
   - Developing plans for how the mine will respond to different situations and hazard assessments.

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APPENDIX. CHARACTERISTICS OF MINES VISITED BY NIOSH DURING THE DEEP COVER STUDY.

Mine Number	Maximum Depth of Cover (ft)	Mining Height (ft)	Primary Support Length (ft)	Extra Intersection Support	CMRR	Pillar Extraction Cut Sequence
1	1,200	7.0	4	Yes	55	Xmas
2	1,200	6.0	6	Yes	45-55	Xmas
3	1,500	6.0	5	Yes	45	Xmas
4	1,100	8.0	6-8	Yes	62	Xmas
5	1,150	5.0	5	Yes	45	Xmas
6	1,050	8.0	4-5	Yes	50	Xmas
7	2,050	5.5	6	Yes	45	Xmas
8	1,700	11.5	6	Yes	50	Xmas
9	1,700	5.0	4	Yes	60	Xmas
10	1,200	5.0	4-5	Yes	45	Xmas
11	2,000	5.5	5	Yes	45-60	Xmas
12	1,150	6.5	5	Yes	45	Xmas
13	1,200	6.0	5	Yes	55	Xmas
14	2,000	5.0	5	Yes	65	Xmas
15	1,740	7.3	5	Yes	51	Xmas
16	1,200	7.0	5	Yes	45	Outside Lift
17	1,150	6.0	5	Yes	45	Xmas
18	1,150	4.1	4	No	55	Outside Lift
19	2,000	15	5	Yes	55	Xmas
20	1,100	7.0	5	No	55	Xmas
21	1,700	13	4	Yes	65	Xmas
22	1,200	6.0	5	Yes	45	No current plan
23	1,050	6.0	4	Yes	55	Xmas
24	1,600	6.5	7	No	45	Xmas
25	1,130	8.0	5	Yes	50	Xmas
26	1,600	5.5	5	Yes	42	Xmas
27	1,200	6.5	4	Yes	54	Xmas
28	1,100	7.0	5	Yes	45-60	Xmas
29	1,700	5.5	4	No	70	Xmas
30	1,300	7.0	5	Yes	45	Xmas

Mine Number	Leave Final Stump?	Size of Final Stump (ft)	Lifts from Crosscut	Type of Standing Support	Continuous Haulage	Rib Bolts	Inside Control Bolter
1	Yes	10x10	Taken last	MRS	No	No	No
2	Yes	8x8	Taken last	Timber	No	No	No
3	Yes	8	No	Timber	No	No	No
4	No	None	Taken last	MRS	No	Yes	Yes
5	Yes	6x6	No	MRS	No	No	No
6	Yes	6x6	Yes	MRS	No	No	No
7	Yes	8x8	Taken last	MRS	No	No	No
8	Yes	10x10	Taken last	MRS	No	No	No
9	Yes	10x10	Taken last	MRS	No	No	No
10	Yes	8x8	Taken last	MRS	No	No	No
11	Yes	5x10	Taken last	MRS	Yes	Yes	Yes
12	Yes	6	No	MRS	No	No	No
13	No	None	Taken last	MRS	No	Yes	Yes
14	Yes	5x10	Taken last	MRS	Yes	Yes	Yes
15	Yes	10x8	Taken last	Timber	No	No	No
16	No	None	All	Timber	Yes	No	No
17	Yes	6	No	MRS	No	No	No
18	No	None	All	Timber	Yes	No	No
19	Yes	10x10	Taken last	MRS	No	Yes	Yes
20	No	None	First	MRS	No	Yes	No
21	Yes	8x8	Taken last	MRS	No	No	No
22	-	-	-	MRS	No	No	No
23	Yes	6	No	MRS	No	No	No
24	Yes	12x12	Taken last	MRS	No	No	Yes
25	Yes	8x8	Taken last	MRS	No	No	Yes
26	Yes	8x8	Taken last	Timber	No	No	No
27	Yes	10x10	Taken last	MRS	No	Yes	No
28	No	None	Taken first	MRS	No	Yes	No
29	Yes	8x8	Yes	MRS	No	No	No
30	Yes	8x8	Yes	MRS	No	Yes	No