MULTIPLE-SEAM MINING IN THE UNITED STATES: BACKGROUND

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INTRODUCTION

Studies have estimated that 156 billion tons of coal, representing two-thirds of the minable reserves in the United States, are subject to multiple-seam mining [Singh and Dunn 1981]. In some U.S. coalfields, particularly in central Appalachia and the West, the majority of today's mines are operating above and/or beneath previously mined seams.

The effects of multiple-seam interactions can include roof falls, rib spalling, and floor heave, which can seriously disrupt mining operations and threaten the safety of miners. In early 2006, a West Virginia coal miner was killed by rib roll that occurred in a high-stress zone beneath a remnant structure in an overlying mine [MSHA 2006].

Fortunately, not every multiple-seam situation results in hazardous conditions. Indeed, the vast majority do not. Accurate prediction of which interactions are likely to be higher-risk allows mine planners to prepare for them or avoid them.

Over the years, multiple-seam mining has been the subject of much research, both in the United States and abroad. Much advice on how to mitigate the risk has been presented, but unfortunately it is often contradictory. For example, one group of researchers wrote that "stresses from superincumbent workings are not transferred through shale strata for distances of over 110 ft" [Haycocks et al. 1982], while another group indicated that "a stress transfer distance of 760 ft has been recorded between longwalls" [Haycocks et al. 1992].

For the past several years, the National Institute for Occupational Safety and Health has been conducting research to develop better techniques for predicting the location and severity of multiple-seam interactions. During this investigation, more than 50 mines were visited across the U.S. coalfields. The study also made extensive use of numerical models, particularly the LaModel family of software [Heasley and Agioutantis 2007]. This paper presents the background to that study. The results of the study are discussed by Mark et al. [2007].

BACKGROUND

Figure 1 shows the five major underground coal mining regions in the United States. From the standpoint of multiple-seam mining, by far the most significant coalfield is the central Appalachian region of southern West Virginia, eastern Kentucky, and southwestern Virginia. Currently, underground mines in this region produce approximately 123 million tons of coal per year, or about 33% of the total U.S. underground production [EIA 2006]. Mining has been ongoing in central Appalachia for nearly 150 years. Recent studies have indicated that perhaps 70% of the ultimate reserve base in the region has already been mined [Bate and Kvitkovich 2004].

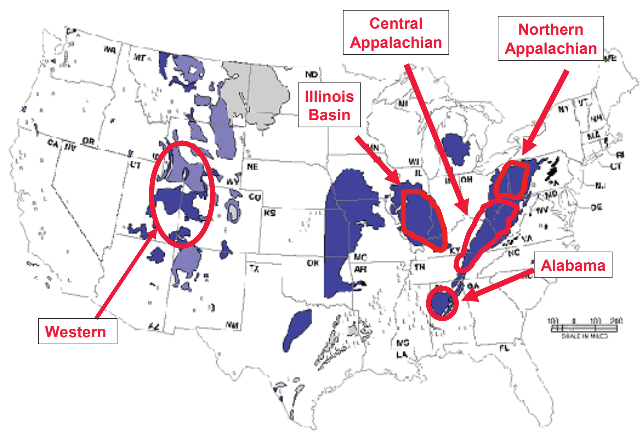

Figure 1.—The five major underground coal mining regions in the United States.

One consequence of the maturity of the central Appalachian coalfields 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 located above, below, and adjacent to today's and tomorrow's operations. Figure 2 shows a typical geologic column from the central Appalachian region. On this property there are 13 seams in which mining has been or is currently being conducted.

Full extraction is also widely practiced in the central Appalachian coalfields. Although only 8 mines currently use the longwall method [Fiscor 2006], a recent survey indicated that approximately 315 mines, accounting for 58% of the room-and-pillar production in the region, engage in pillar recovery [Mark et al. 2003]. The prevalence of full extraction adds greatly to the potential for multiple-seam interactions.

The Western United States is the next most significant area for multiple-seam mining. In Utah, Colorado, Wyoming, and New Mexico, nearly 95% of underground

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production comes from 13 longwall operations [EIA 2006; Fiscor 2006]. Approximately half of these are operating in multiple-seam configurations. In contrast to central Appalachia, in the West the same mining company is usually responsible for all the mining on a property. As a result, a greater degree of multiple-seam planning is normally possible. On the other hand, when combined with deep cover and strong roof and floor rock, multiple-seam interactions can contribute to deadly bump hazards [Peperakis 1968; Iannacchione and Zelanko 1995].

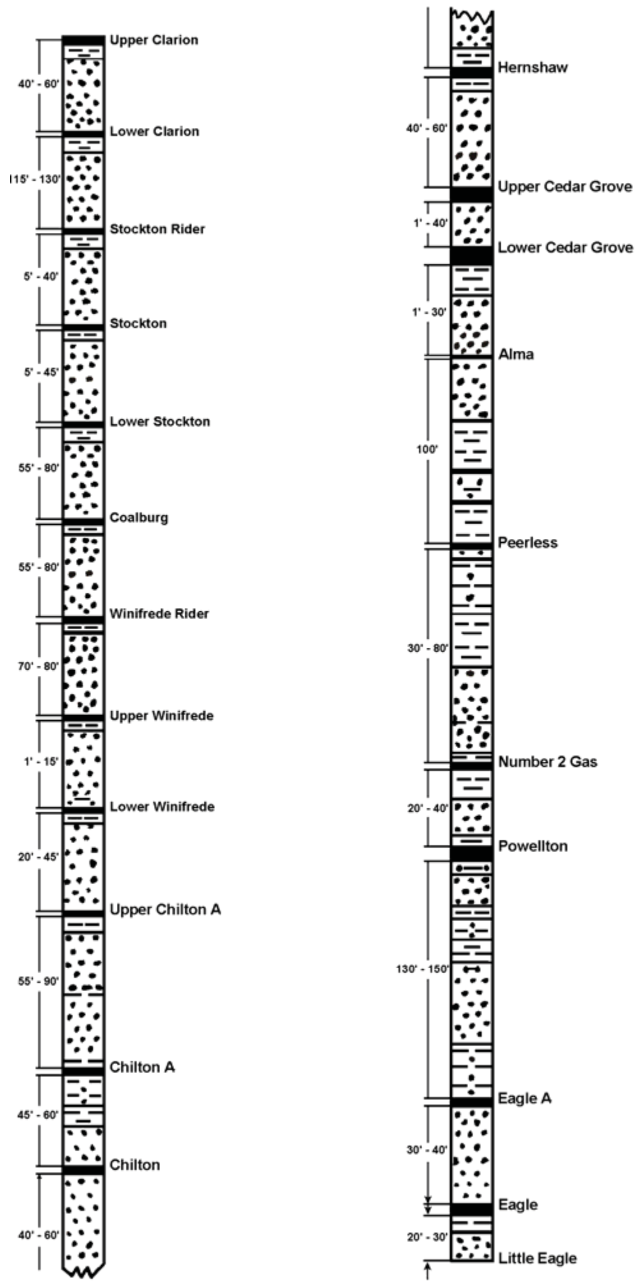

Figure 2.—Typical geologic section for Boone County, WV, showing coal seams.

In none of the other three underground mining regions are multiple-seam interactions currently a major factor, although all three historically have had problems [Kohli 1992; Paul and Geyer 1932; Zachar 1952], and they may very well have them again in the future. Factors that contribute to the relative lack of multiple-seam interactions in these regions include the following:

- Most longwall production in the northern Appalachian and Alabama coalfields is from a single seam (the Pittsburgh and Blue Creek Seams, respectively), without significant mining in other seams above or below.
- The depth of cover, particularly for room-and-pillar mines, is relatively low in northern Appalachia and the Illinois Basin.
- Very few room-and-pillar mines engage in full-extraction pillar recovery in the Illinois Basin. There is almost no room-and-pillar mining at all in Alabama.

HAZARDS ASSOCIATED WITH MULTIPLE-SEAM MINING

Ground instability is usually the greatest hazard due to multiple-seam interaction. Interactions may be classified into four major categories depending on the mining method, mining sequence, and thickness of the interburden. Other potential hazards are associated with water, gas, and oxygen-deficient air.

Undermining, the first category of interaction, occurs when the upper seam has been mined first and the lower seam is the active seam (Figure 3). In an undermining situation, damage is caused by load transfer from highly stressed remnant structures associated with full-extraction mining in the overlying seam. These remnant structures can generally be classified as either:

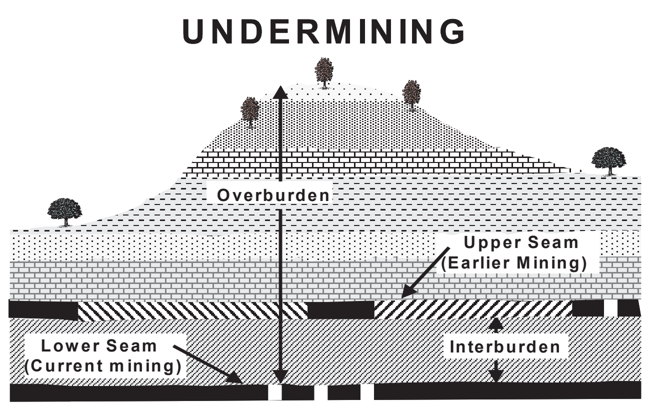

Figure 3.—Undermining interaction.

- *Gob-solid boundaries*, with gob on one side; or
- *Isolated remnant pillars* that are surrounded by gob on two or more sides (Figure 4).

Figure 4 shows that while a gob-solid boundary carries a single, distributed abutment load, an isolated remnant pillar is subjected to two overlapping abutments.

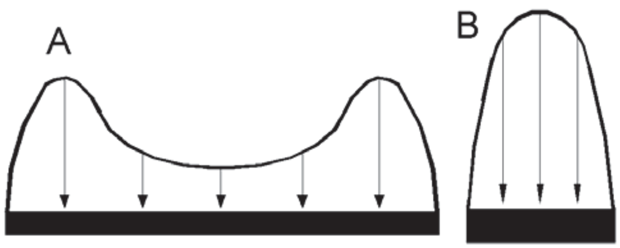

Figure 4.—Stress concentrations in multiple-seam mining: (A) gob-solid boundaries associated with a very large pillar and (B) remnant pillar isolated in the gob.

As a result, the stress concentration on an isolated remnant pillar is usually significantly larger than that on a gob-solid boundary, and its impact on underlying seams is proportionally greater. The interburden thickness is also important because the stress concentration beneath any upper-seam remnant structure becomes less intense the greater the interval between the seams.

Overmining, the second type of interaction, occurs when the upper seam is extracted after mining is complete in the lower seam (Figure 5). Load transfer occurs in this situation just as it does in undermining (in other words, gob-solid boundaries and isolated remnant pillars cause stress concentrations both above and below). In addition, however, full extraction of the lower seam normally results in subsidence of the overlying beds.

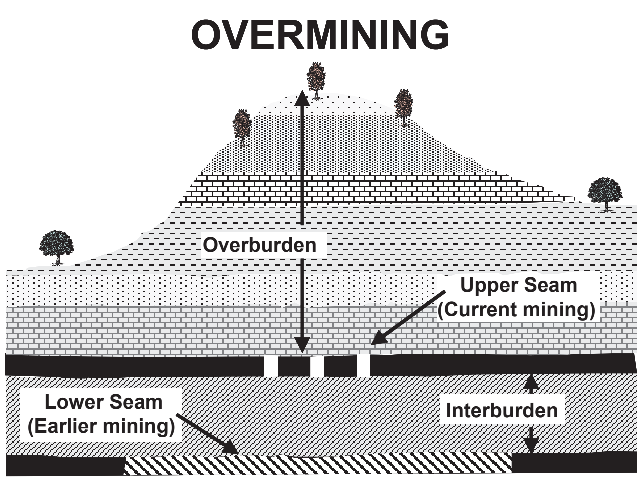

Figure 5.—Overmining interaction.

Figure 6 is a conceptual model that illustrates the type of damage that can be expected within the overburden due to subsidence above a full-extraction panel. Five broad zones can be identified [Singh and Kendorski 1981; Peng and Chiang 1984; Kendorski 1993, 2006]:

1. The *complete caving zone*, in which the roof rock is completely disrupted as it falls into the gob, normally extends two to four times the extracted seam height (h).
2. The *partial caving zone,* in which the beds are completely fractured but never lose contact with one another, extends up to 6–10 h.
3. The *fracture zone,* within which the subsidence strains are great enough to cause new fracturing in the rock and create direct hydraulic connections to the lower seam. The top of this zone can be as high as 24 h above the lower seam.
4. The *dilated zone,* where the permeability is enhanced but little new fracturing is created, extends up to 60 h.
5. The *confined zone,* where subsidence normally causes no change in strata properties other than occasional bed slippage. This zone extends from the top of the dilated zone to about 50 ft below the surface.

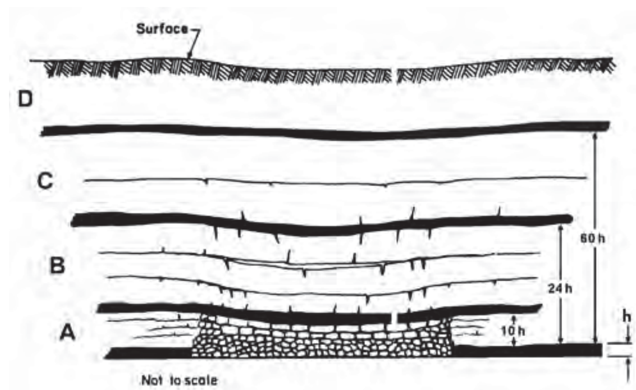

Figure 6.—Overburden response to full-extraction mining: (A) caving zones, (B) fracture zone, (C) dilated zone, and (D) confined zone.

The dimensions of these zones vary from panel to panel because of differences in geology and panel geometry. The implication of this model for multiple-seam mining is that when the interburden thickness exceeds approximately 6–10 times the lower seam thickness, the upper seam should be largely intact, although the roof may be fractured or otherwise damaged.

Dynamic interactions occur whenever active mining occurs above or beneath open entries that are in use. The most severe dynamic interactions occur when a lower seam is longwalled or pillared, resulting in active subsidence of the open overlying workings. However, damage can also be caused by the abutment stresses associated with full extraction in an overlying seam or even, in extreme cases, by development mining above or below.

The conditions associated with dynamic interactions are generally far more difficult than would have been the case if the open workings were developed after the full extraction was completed. Part of the explanation is that a dynamic interaction subjects the preexisting works to a traveling wave of subsidence and/or abutment stress rather than the static situation where the disturbance is concentrated in a single area. In addition, while unmined ground is normally in a confined state when it is overmined or undermined, the presence of a mine opening removes the confinement. The loss of confinement greatly weakens the rock mass and exposes it to tensile bending stresses.

Ultraclose mining is the fourth type of interaction and the only one in which development mining alone is significant. The main concern is failure of the interburden between the two seams. The beam of interburden can fail either through shear caused by pillar punching or by tension caused by the self-weight of the rock plus that of any machinery working on it (Figure 7). Ultraclose interactions are unlikely when the two seams are more than 20–30 ft apart [Haycocks and Zhou 1990; Singh et al. 2002]. Ultraclose scenarios are most likely to occur near where a thick seam splits or where a rider coalbed is of minable thickness.

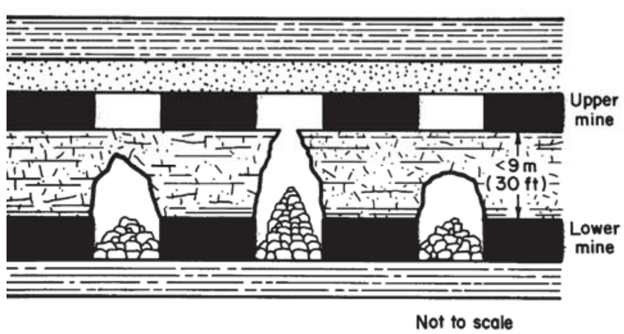

Figure 7.—Ultraclose mining (after Chekan and Listak [1994]).

Other hazards include the potential for inundation from an overlying flooded mine, particularly where full extraction in the lower seam can create a direct pathway between the upper- and lower-seam gobs. Mine Safety and Health Administration (MSHA) regulations require that a permit be obtained prior to mining under a body of water. An evaluation of the potential hazard should consider [Michalek and Wu 2000]:

- Estimates of the potential volume of water in the overlying mine;
- Evaluation of the strata separating the two mines;
- Determination of probable flow paths and identification of critical areas that may become flooded;
- A warning system, water control plan, and evacuation plan in the event of an inundation.

A review of MSHA data indicates that of the 201 inundation incidents that were reported during 1996–2005, only 4 resulted when caving associated with full extraction in a lower seam intersected water-filled overlying workings. Several other water inundations occurred when development in a lower seam inadvertently cut into uncased boreholes that were connected with an upper seam. No injuries were associated with any of these incidents. In one incident, however, the first longwall panel at a Kentucky mine encountered a major inflow from workings 150 ft above. The water posed no hazard to the miners, but the lack of pumping capacity in the lower seam resulted in major mining delays [Mark et al. 1998].

Interestingly, development *above* gob areas has been associated with large, but temporary groundwater inflows in several instances [Stansbury 1981; Bauer et al. 1992; Lazer 1965]. In these cases, the fracture and dilated zones apparently filled with excess groundwater, which was drained when the entries were developed. Fractures in these zones can also fill with methane or oxygen-deficient air, resulting in inflows of methane or blackdamp when they are intersected by overmining.

Overmining

During the hand-loading era, which lasted until about 1950, most underground coal mines operated under shallow cover and emphasized complete recovery, leaving few remnant structures in the gob. Perhaps as a result, early studies of multiple-seam interactions barely mentioned undermining and focused almost exclusively on overmining.

One of the first comprehensive studies was reported by Eavenson [1923a]. He concluded that “mining an upper seam after a lower one can almost always be successfully done when the interval between the seams exceeds 19 ft,” although he noted several cases where some coal had to be abandoned with interburdens up to 120 ft. Several other individuals, including such notable rock mechanics pioneers as D. Bunting and G. S. Rice, took partial exception to Eavenson’s conclusion, pointing out the importance of the nature of the interburden, thickness of lower bed, and uniformity of extraction of the lower bed [Eavenson 1923b]. Taking all the evidence into consideration, the American Institute of Mining and Metallurgical Engineers, Committee on Ground Movement and Subsidence, concluded that Eavenson’s figure of 19 ft was appropriate as long as the thickness of the lower seam did not exceed 8–9 ft [AIMME 1926].

The next significant investigations of multiple-seam mining were conducted at Virginia Polytechnic Institute and State University (VPI) in the early 1950s by C. T. Holland and his student D. T. Stemple. Initially, Holland seemed to draw optimistic conclusions similar to those of Eavenson. Citing 38 examples from the literature, he concluded that "all but two or three" were successful, although "success" was defined as extracting as little as 50% of the upper seam [Holland 1951]. Holland found that 20–25 ft of interburden was adequate to provide good mining conditions, although he emphasized that "no remnants should be left in the lower seam" because remnants are "certain to result in considerable disturbance to the overlying strata." Holland also emphasized that at least 3 months, and preferably several years, should elapse after completion of mining in the lower seam to allow settlement of the gob to be complete [Holland 1951].

The study by Stemple [1956] was a landmark. He visited 45 mines throughout the eastern coalfields and ultimately collected a database of 61 actual mining case histories. About one-third of these were overmining cases, and Stemple found that in nearly every one there was some disturbance to the overlying seam, including:

- Cracking or horizontal parting of the roof strata;
- Vertical displacement (subsidence);
- Rarely, but serious when it occurred, "squeezing and crushing of coal, accompanied by falls of top or heaving of the bottom."

Stemple found that the most severe damages occurred directly above isolated remnant pillars abandoned in the underlying seam. Gob-solid boundaries also caused trouble, but the greatest disturbance was typically observed "not directly above the gob edge, but rather 100–300 ft out over the goaf."

Stemple concluded that Eavenson's recommendation of 19 ft of interburden might have been adequate for hand-loading, but that "such conditions would probably be prohibitive to mechanized mining." Indeed, he found that "damage seriously adverse to mining can be done even with a vertical interval greater than 300 ft."

One explanation for the discrepancy between the conclusions of Stemple and Eavenson is that they may have been talking about different things. Eavenson was apparently concerned with mining over gob areas, which were usually quite extensive in hand-loading operations. As mechanized mining became more prevalent, remnants of various shapes and sizes were more often left within the gob areas. In addition, the new mining methods were less flexible, so when working an overlying seam it became much more difficult to avoid the underlying remnants. The result was that even though mining above gob areas might still be feasible, finding enough good mining to make extracting an overlying seam profitable became much more challenging.

One other factor Stemple evaluated was the effect of time. He concluded that mining in an overlying seam should not be conducted until the subsidence process is completed, which could require 5–10 years.

The next major study of multiple-seam mining was conducted by C. Haycocks and his students and colleagues at VPI. This work was conducted over a period of nearly 2 decades, beginning in the early 1980s. Haycock's program included the development of empirical equations based largely on Stemple's data, supplemented by analytic work, photoelastic studies, and numerical modeling. There is little evidence, however, of underground in-mine data collection in Haycock's work. Haycock's research resulted in an extensive published literature, as well as several mine design computer programs.

To evaluate the potential for successful overmining, several equations were proposed [Haycocks and Zhou 1990]:

$$I_{co} = h/t\,[18.84\,X - 2(Z - 50) - 1{,}240] \quad (1)$$

$$I_{co} = h\,(3.5X - 224) \quad (2)$$

$$I_{co} = h/t\,(15X - 973) \quad (3)$$

where I_{co} = critical interburden thickness (ft) for no appreciable damage to upper seam;
h = lower-seam thickness (ft);
t = time since mining the first seam (years);
X = percent extraction in the lower seam;
and Z = percent hard rock in the interburden.

Equation 2 indicates that the critical interburden thickness ranges from zero (for a lower-seam extraction of about 65%) to as much as 700 ft (for 90% extraction in an 8-ft lower seam).

Application of these equations presents several problems. First, it is not made clear where they should be applied—above an isolated remnant pillar, a gob-solid boundary, or anywhere the lower seam has been mined out? Second, where should one determine the percent extraction in the lower seam? Is it an overall percent extraction, or does it vary from place to place? Finally, Equations 1 and 3 are very sensitive to the time factor, but does it make sense that critical interburden thickness is reduced by a factor of 10 if a fully subsided gob is 50 years old rather than 5?

Luo et al. [1997] looked back on the earlier VPI studies and concluded that "although efforts were made to relate the magnitude of upper-seam damage to innerburden thickness, mining height, time, and extraction percentage, the data scatter was too great to achieve this relationship." Further research also showed that "upper-seam damage could not be correlated with subsidence strain at the upper-seam elevation." More success was reportedly achieved when the upper-seam roof conditions were included together with vertical movement in the upper seam.

Several case histories of overmining, successful and unsuccessful, have been reported in the literature during the past 3 decades. In the Gary District of southern West Virginia, U.S. Steel attempted to work the Pocahontas No. 4 and 5 Seams about 60 ft above the worked-out No. 3 Seam [Stansbury 1981]. Conditions were extremely difficult, particularly in the No. 4 Seam where the roof consisted of "3–17 ft of unconsolidated and thinly laminated bands of shale intermixed with thin bands of coal." Particular difficulties occurred "when mining near or directly above gob lines or lost blocks of coal in the No. 3 Seam." Ground control was reportedly achieved by developing 12-ft-wide entries supported by 9-ft bolts and trusses, both on 3-ft centers, but the roof support cost made mining uneconomic. Mining was significantly easier in the No. 5 Seam, typically just 10 ft above the No. 4, and the difference was attributed to a more competent shale roof.

In central Pennsylvania, Bethlehem Mines Corp.'s No. 33 Mine employed longwall methods to extract the B Seam and the overlying C-prime Seam [Bauer et al. 1992]. The B Seam, averaging about 5 ft thick, was extracted first, and the interburden was approximately 105 ft. The depth of cover was typically less than 600 ft, which allowed the upper-seam gates to be stacked above the lower ones. Ground conditions in the upper seam were generally quite good, indeed better than areas where the upper seam was mined over virgin B Seam. The improvement was attributed to subsidence above the lower-seam longwalls that apparently relieved some of the in situ horizontal stress. Some minor areas of poor roof were encountered when crossing into areas above the gob, but these could be handled with some additional support. Water inflows were a more serious impediment to upper-seam mining.

In eastern Kentucky, Black Mountain Resources used room-and-pillar techniques to extract Owl Seam reserves located 200–235 ft above abandoned Harlan Seam longwall panels [Rigsby et al. 2003]. The Harlan Seam was 11 ft thick with up to 1,500 ft of cover. The Owl Seam panels were driven across the longwall stopline pillars and then developed over the longwall gob. Although some roof fractures, rib spalls, and water inflows were observed, the panel was developed and retreated without major incident.

Undermining

Although undermining is more common than overmining and although it is the recommended mining sequence, it has received considerably less attention in the literature than overmining. The explanation may be the apparent simplicity of the load transfer effect. For significant load transfer to occur, two factors must be present:

- The interburden must be relatively thin; and
- The seams must be relatively deep.

Stemple [1956] included 26 cases of undermining in his study, and he documented interactions in about half of them. In those cases where interactions occurred, the depth of cover exceeded 500 ft and the interburden was less than 110 ft. The disturbances all occurred beneath isolated remnant pillars or within 100–200 ft of a gob-solid boundary. Stemple also concluded that the time lag after the mining of the upper seam was not a factor in undermining.

Haycocks et al. [1982] emphasized the role of the interburden geology in determining the extent of load transfer. A softer overburden, either due to a large number of rock layers or a low modulus of the individual layers, results in an elongated pressure bulb that reaches deeper seams below. Using Stemple's data, Haycocks et al. [1982] proposed two relationships for predicting the critical interburden thickness (I_{cu}) in room-and-pillar mining:

$$I_{cu} = 110 - 0.42\,Z \qquad (4)$$

$$I_{cu} = 6.8\,N + 55 \qquad (5)$$

where N = the number of interbeds;
and Z = percent hard rock in the interburden.

Equation 4 is illustrated in Figure 8. Elsewhere, Haycocks and Zhou [1990] emphasized the special role of isolated remnant pillars, including longwall chain pillars, in creating high-pressure zones in seams above or below. Pillars less than 60 ft wide were singled out as allowing the "abutment pressure zones from both sides to superimpose."

In European mines, multiple-seam interactions have been a major concern for many years due to the deep cover and long history of mining. In the 1970s, the U.K. National Coal Board collected detailed data from 18 undermining case histories [Dunham and Stace 1978]. Using multivariate statistical techniques, the study concluded that the two most important factors affecting the condition of the underlying seam during longwall extraction were:

- The type of remnant structure; and
- The initial roadway stability (determined rock strength, roadway width, depth of cover, width of the adjacent pillar, and other factors).

Dunham and Stace cautioned that it is "extremely dangerous to dismiss interaction effects purely on the basis of the thickness of the interval between the seams." In one case in their database, an isolated remnant pillar caused a disturbance 450 ft below, while in another case, a gob-solid boundary had no noticeable effect just 90 ft below.

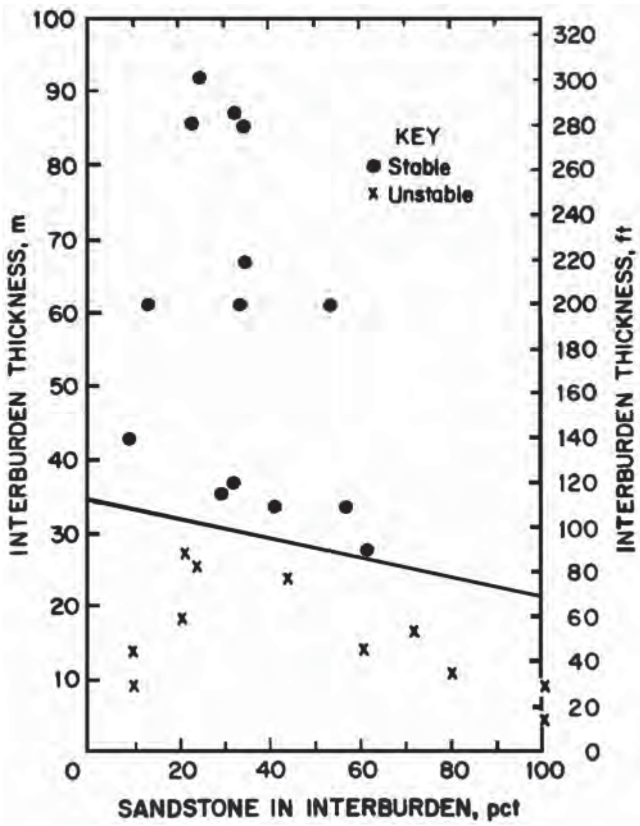

Figure 8.—Percent sandstone in interburden versus interburden thickness (after Haycocks and Zhou [1990]).

Dynamic Interactions

For nearly a century, the verdict of the experts on dynamic interactions has been unanimous: Don't do it! Some examples follow:

- Eavenson [1923a]: "Working in an upper seam should not be attempted while pillar robbing is going on beneath it."
- Paul and Geyer [1932]: "Pillar recovery should never be commenced under advance work in the overlying seam."
- Stemple [1956]: "The greatest difficulties are caused when pillar falls are made in the lower seam beneath previously developed entry work in the upper seam."
- Lazer [1965]: "If openings are first developed in the upper seam and then undermined, the openings in the upper seam will cave totally and the developed pillars will be lost."

Despite these warnings, this practice is still occasionally tried, with depressing results. Three relatively recent cases have been reported in the literature—one where pillars were extracted beneath previously developed mains 180 ft above [Su et al. 1986] and two where longwalls were extracted as far as 550 ft beneath open main entries [Ellenberger et al. 2003; Mark 2006]. In each case, the overlying main entries were lost or severely damaged.

Less predictable are instances in which delayed subsidence of underlying works has the same destructive effect on overlying entries. In one instance, a set of mains was developed 180 ft above pillared works, and conditions were excellent for 2 years [Mark 2006]. Then the roof began to deteriorate dramatically, and heavy supplemental support was required to prevent major roof collapses. In another instance, dewatering of 20-year-old works caused marginally stable support pillars to fail, causing a pillar collapse in an overlying seam and subsidence at the surface [Kohli 1992]. In yet a third case, extensive floor heave developed in a lower seam 2 years after it was developed. A year later, the 5-year-old workings in the upper seam were severely damaged [Matetic et al. 1987].

Although subsidence associated with full extraction in a lower seam has the most dramatic effects, dynamic interactions have also been attributed to full extraction in an upper seam [Hill 1995]. In this situation, because the stress abutments are applied to the unconfined strata around preexisting openings in the lower seam, their effects are more severe than would be the case if the upper-seam mining was complete before the lower seam was developed.

Ultraclose Mining

Haycocks and Zhou [1990] stated that "when the interburden thickness is less than two times the room width, interburden failure cannot be ruled out." Typically, however, ultraclose interactions are only a concern when the interburden is less than 25 ft. Zhou and Haycocks [1989] determined that the minimum safe working thickness for a massive, unstratified sandstone was just 6 ft, whereas for shale it was 20 ft. They also determined that tensile failure is unlikely when the interburden thickness exceeds about 4 ft, so shear failure is the main concern.

Columnization of the pillars is considered the standard design practice when ultraclose interactions are a concern. Columnization minimizes the shear stress in the interburden and also provides a more uniform stress on the pillars, minimizing the risk of pillar failure. In Indian coal mines, columnization is required if the interburden is less than 30 ft [Singh et al. 2002]. In South Africa, columnization is recommended where the parting distance is less than 0.6–0.75 times the pillar center-to-center distance. Barrier pillars should be columnized for interburdens up to 100 ft thick [Munsamy et al. 2004].

NUMERICAL MODELING FOR MULTIPLE-SEAM MINING

Analysis of multiple-seam mining interactions is complex because of the many geologic and mine design variables, as well as the complicated three-dimensional (3–D) geometries that occur. This complexity makes empirical analysis difficult and lends attractiveness to numerical approaches. Two main types of numerical model have been employed for multiple-seam analysis:

- *Displacement-discontinuity* models, including MULSIM and LaModel, in which only the seams of interest are discretized; and
- *Finite-element* models, in which the entire rock mass must be discretized.

Displacement-discontinuity models provide a pseudo-three-dimensional simulation of tabular deposits such as coal. They have undergone continuous development and improvement over the past 2 decades. The original MULSIM and MULSIM–PC codes were limited to purely elastic analyses [Donato 1992]. MULSIM–NL allowed yielding of elements within the coal seams and nonlinear gob elements [Zipf 1992], but the overburden was still simulated as one solid material. LaModel introduced a formulation that simulates the overburden as a stack of layers with frictionless interfaces, thereby providing a more realistic suppleness to the strata response [Heasley and Chekan 1999]. LaModel can also consider topographic relief and subsidence, and LaModel grids can be generated directly from AutoCAD mine maps [Heasley and Agioutantis 2007]. The most recent development is a simplified two-dimensional (2–D) version of LaModel called LaM2D, which is much easier to grid and which runs in a fraction of the time required for the full 3–D model [Akinkugbe and Heasley 2007].

Chekan and Listak [1993, 1994] employed MULSIM–NL in an extensive series of parametric studies evaluating the effects of mining sequence and orientation on multiple-seam interactions. Their most significant findings were:

- Peak multiple-seam stresses are greater when retreating from solid toward the gob than when retreating from the gob to the solid (Figure 9);
- Stresses on the longwall face are greatest when the face is being retreated in a direction directly perpendicular to a remnant structure in the other seam; and
- Orientation relative to other seam remnant structures is not a major factor for development workings.

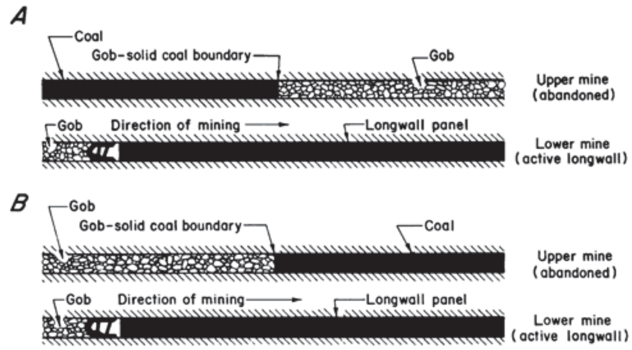

Figure 9.—Influence of retreat direction on multiple-seam interaction: (A) retreating from solid to gob creates an unfavorable "stress window," while (B) retreating from gob to solid results in lower stress concentrations (after Chekan and Listak [1993]).

Heasley and Chekan [1999] report two case histories in which LaModel was used to evaluate multiple-seam interactions. In both cases, the model results were calibrated against extensive stress mapping that was conducted underground. In the first instance, an undermining example from eastern Kentucky, a 60-ft-wide isolated remnant pillar in the upper seam resulted in a multiple-seam stress of 2,200 psi, which, when added to the 3,000-psi single-seam pillar stress, was enough to cause significant roof and rib failure (Figure 10). In the other case, a set of longwall gates encountered multiple-seam stresses of 1,300 psi above a barrier adjacent to high-extraction room-and-pillar mining. A significant feature of this study was that it was necessary to simulate the yielding of the lower-seam production pillars in order to realistically model the interaction.

Su et al. [1986] report an early example of the use of finite-element modeling to investigate multiple-seam interactions. Both 2–D and 3–D models were employed, and some allowed bedding plane slip. One significant conclusion was that caving of the lower-seam roof strata forced the horizontal stresses upward, potentially creating stress concentrations around openings in the upper seam. The models also showed that highly bedded rock, where sliding takes place along individual layers, results in a narrower and deeper zone of interaction.

Hsiung and Peng [1987a] used numerical modeling to develop some rules of thumb for undermining. They concluded that if the interburden thickness is two to three times the width of the upper-seam isolated remnant pillar, no interaction is likely to occur. On the other hand, when the interburden is less than 10 times the mining height of the upper seam, the models indicated that the lower seam is likely to be fractured as well as highly stressed. Hsiung and Peng [1987b] also indicated that it is best to retreat from the gob toward the solid and that the best situation occurs when a longwall face maintains an approach angle of about 30° to remnant structure.

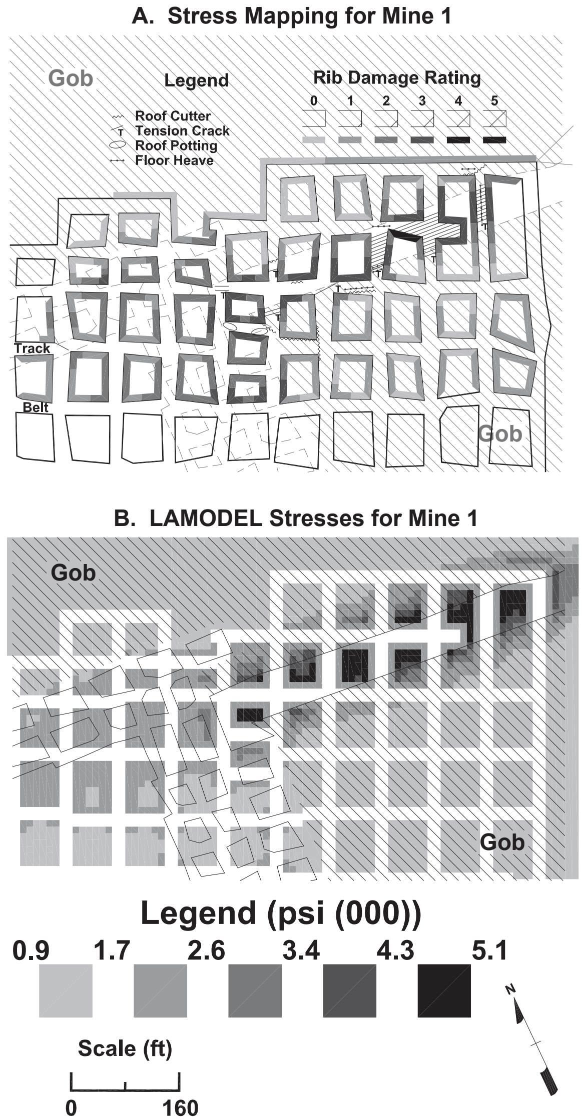

Figure 10.—Comparison between (A) in-mine stress mapping and (B) LaModel-calculated stresses for eastern Kentucky (after Heasley and Chekan [1999]).

Some recent examples of finite-element modeling applications to multiple-seam mining include 2–D and 3–D analyses of pillar and roof stability in overmining cases from northern West Virginia [Zhang et al. 2004; Morsy et al. 2006]. Zipf [2007] focused on the effects of vertical stress, horizontal stress, stress reorientation, and bedding slip on failure mechanics during multiple-seam mining. Gale [2004] evaluated different stacked longwall chain pillar layouts in the Australian context and concluded (as have many others) that the offset arrangement is far superior to vertical stacking. His models also predicted that stress transfer might be observed up to four pillar widths above and below a chain pillar, which would be approximately 400 ft for a typical Australian longwall design.

SUMMARY AND CONCLUSIONS

Hazards resulting from multiple-seam interactions are a serious issue at many U.S. coal mines, particularly in the central Appalachian and western mining regions. The four types of interaction are:

- *Undermining*, where stress concentrations caused by previous full extraction in an overlying seam is the main concern;
- *Overmining*, where previous full extraction in an underlying seam can result in stress concentrations and rock damage from subsidence;
- *Dynamic interactions*, caused when full extraction takes place above or below open entries that are in use (the most extreme dynamic interactions involve mining beneath open entries in an upper seam); and
- *Ultraclose mining*, where room-and-pillar development of two seams within 25–30 ft of each other can result in interburden failure.

Undermining and overmining are by far the most common types of interaction. Nearly a century of research has identified a number of factors that can affect the intensity of a multiple-seam interaction. These include:

- *Depth of cover:* The deeper the overburden, the greater the potential stress concentration caused by multiple-seam mining.
- *Mining sequence:* Overmining is more difficult than undermining because of the potential for rock damage caused by subsidence. Dynamic interactions (particularly retreating beneath open works) should be avoided at all costs.
- *Interburden thickness:* The smaller the distance between the seams, the greater the intensity of the potential interaction.
- *Type of remnant structure:* Isolated remnant pillars that are surrounded by gob cause more intense interactions than gob-solid boundaries. First workings are generally not a concern unless the seams are ultraclose.
- *Interburden geology:* Stronger, less bedded interburden tend to distribute multiple-seam stress concentrations more rapidly, resulting in less intense interactions.
- *Immediate roof geology:* Weak roof (and floor) are more likely to be damaged by multiple-seam interactions.
- *Angle of approach to remnant structure:* Retreat mining should proceed from the gob toward the solid side of a gob-solid boundary, and a longwall should not be brought broadside into long remnant structure.

The large number of geologic and mining variables involved in multiple-seam interactions has made them very difficult to analyze. Empirical studies have foundered because the databases were too small for the number of variables and because bivariate analyses are inappropriate when there are so many variables involved. Numerical models have been helpful, but to be most useful they have required site-specific calibration to underground conditions. A hybrid approach, employing multivariate statistical analysis of a large database combined with numerical modeling, could provide the mining community with a valuable tool for predicting, avoiding, or controlling multiple-seam hazards.

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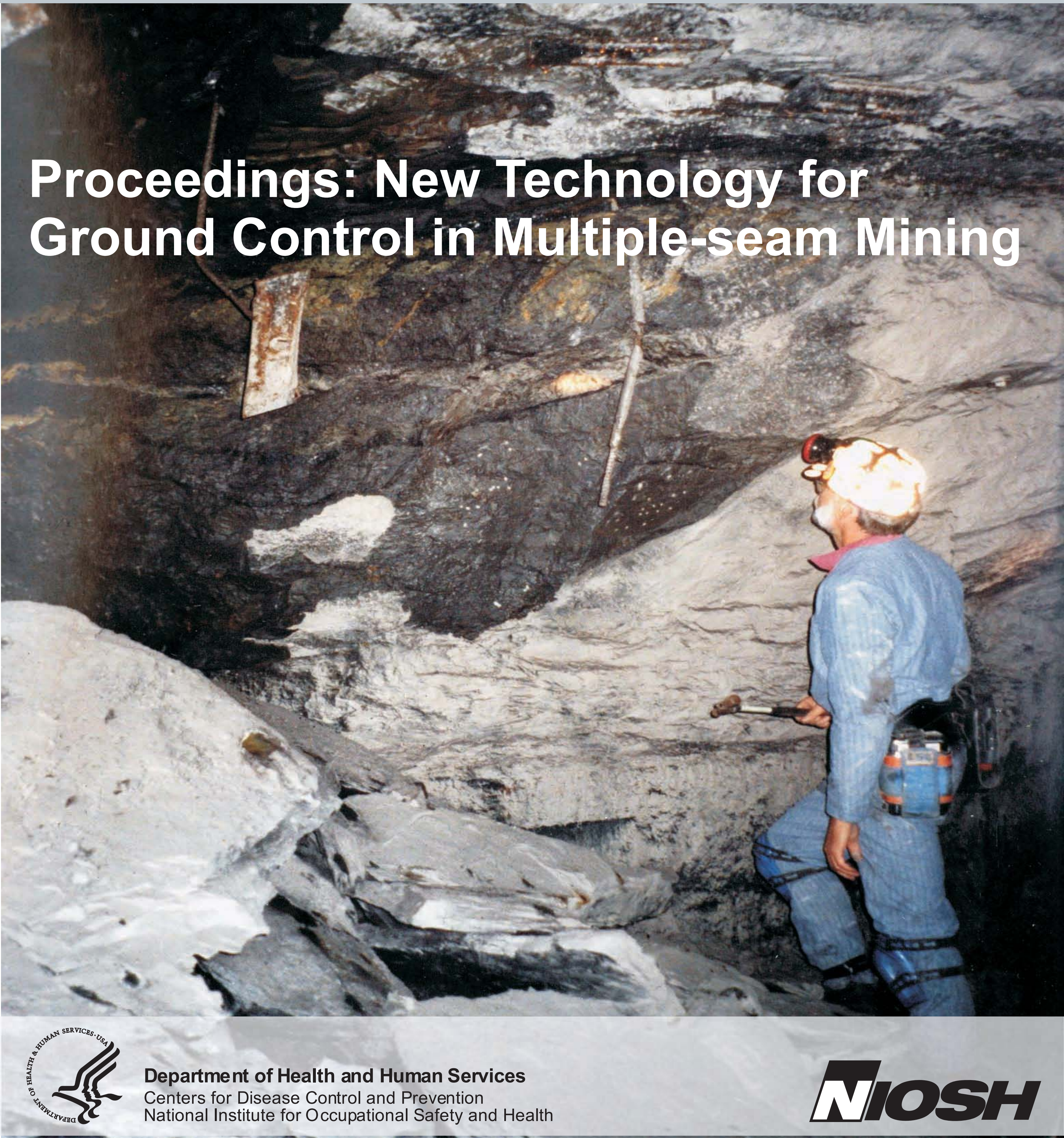

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