PILLAR MECHANICS OF COAL MINE BURSTS: A CONTROL STRATEGY

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ABSTRACT

One of the most difficult and longstanding engineering problems associated with coal mining is the catastrophic failure phenomenon known as coal mine bursts (known in the United States as *bumps*). For more than 70 years, researchers and practitioners have attempted to determine whether this destruction observed underground is caused by stress conditions within the coal pillar or from distant seismic sources in the mine roof and floor strata. The role of confinement and the extent of failure in solid pillars and panels have also proven difficult to define. These are important issues, since control solutions need to be based on a fundamental understanding of the problem.

Observations by U.S. Bureau of Mines researchers over the last decade have helped to clarify certain aspects of these issues. Microseismic sensors and geomechanic field measurements have located areas of excess energy release, identified stress conditions in coalbeds close to failure, and recorded the response of mine structures prone to bursts. In the present study, data available for a range of U.S. bursts were considered in an effort to evaluate both common and distinctive features. Although the attempt revealed little commonality, encouraging results were produced by categorizing coal bursts by source mechanisms. When a coal burst is thus categorized, differences in environmental factors–such as geology, stress fields, and mining methods–are highlighted, and viable control strategies are readily recognized.

INTRODUCTION

Analyses made within this paper were based on numerous burst-related investigations reported over the past 76 years. The earliest of these was made by Watts (1918) at the Sunnyside No. 1 Mine in Utah. Reports by Rice (1935) and Bryson (1936) indicate that coal mine bursts occurred in the Cumberland Field of Kentucky and Virginia as early as 1923 and became very troublesome during the 1930's. In the 1950's, bursts continued to be reported in the eastern and western U.S. coalfields (Holland and Thomas, 1954; Peperakis, 1958; Talman and Schroder, 1958), stimulating the development of burst control strategies and remediation techniques.

The wealth of information developed in the first half of this century provided a strong foundation for expanded research investigations during the last decade. Recent efforts were initiated in response to the persistent occurrence of bursts in U.S. coalfields. Since 1980, 19 underground mines in three Eastern States (figure 1) and two Western States (figure 2) have reported more than 30 coal mine bursts.

Without further development and application of burst control measures, the occurrence of burst-related problems in the United States will likely increase for several reasons. First, full-extraction mining, with both the room-and-pillar and longwall methods, continues to increase. Widespread application of remote control continuous mining machines, continuous haulage, and mobile roof supports have made these methods very attractive. Second, these full-extraction mining methods are working at deeper mining levels with higher stress conditions. Lastly, clean air legislation in the United States has shifted some production to the low-sulfur regions of the southern Appalachian and western coalfields, where much stronger and stiffer strata exist. Strong strata, high stresses, and full-extraction mining are environmental factors long associated with coal mine bursts.

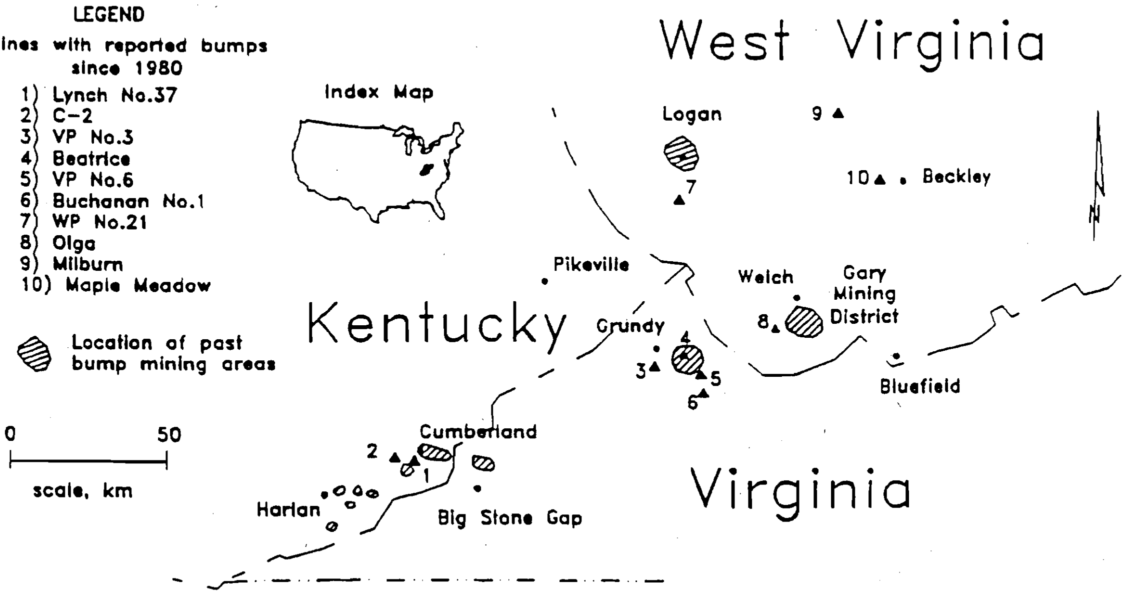

Figure 1.—Coal mine bursts in the Eastern United States since 1980.

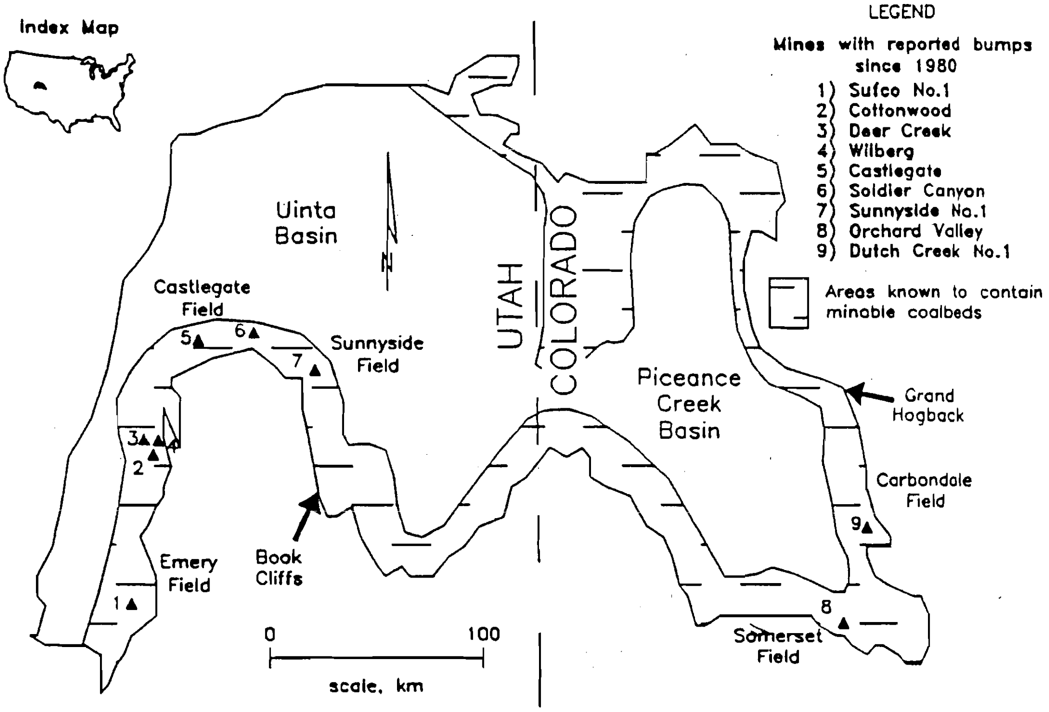

Figure 2.—Coal mine bursts in the Western United States since 1980.

CATEGORIES OF COAL MINE BURSTS

For many years, researchers have acknowledged differences between individual coal mine bursts. Such distinctions seek to explain apparent differences in the manner in which bursts are manifested underground and to incorporate some practical and theoretical considerations of the environments in which these bursts occur. In general, three environmental factors appear to be most influential in the occurrence of bursts: (1) geology, (2) stress, and (3) mining methods.

It has long been known that geology plays an important function in bursts. Sandstone, formed by ancient fluvial processes, is the lithology most commonly identified with bursts. However, to say that sandstone is *needed* for a burst to occur per se would be incorrect. This is because the strength of sandstone rock masses is very diverse. To a large degree, this strength is controlled by geologic discontinuities, which range in scale. Often, the largest-scale discontinuity is the basal contact that is formed by the erosional powers of an ancient river system. The position and extent of this low shear strength surface can vary widely within U.S. burst-prone mine roof strata. Next in scale are trough beds, which represent unique episodes of an individual channel within the greater limits of an ancient fluvial system. The trough beds are generally crescent- (arc) shaped and can extend tens of meters, often intersecting other discontinuities to form a network of potential failure surfaces. These surfaces generally have moderate shear and very low tensile strengths. Smaller discontinuities such as crossbeds, coal stringers, and clay bands occupy scales of up to 1 m and can be found in varying intensity within a fluvial channel depending on which depositional environments were at hand. Shear and tensile strengths of these discontinuities range from low to moderate.

A measure of the effect of these properties on sandstone strength can be demonstrated with the sandstone Unit Rating measurements contained in the Coal Mine Roof Rating database developed by the U.S. Bureau of Mines (Molinda and Mark, 1994). The unconfined compression strength accounts for one-third of the Sandstone Unit Rating, while the other two-thirds is estimated by the intensity of discontinuity spacing and its shear strength. This database shows that sandstones have a nonuniform strength distribution that spans the spectrum of behaviors from very weak to very strong.

The interaction of these discontinuities along with the grain-size characteristics and cementing properties of the sandstones can produce a wide range of responses during the extraction of adjacent blocks of coal. Indeed, some sandstones are known to cave readily, whereas others can bridge tremendous spans of gob. It is therefore not surprising that certain types of sandstones can be associated with specific burst mechanisms. This fact will be alluded to later in this paper.

The next environmental factor–stress–is extremely important in bursts, since it will largely control the states at which the strata will fail. Obviously, high vertical stress conditions can be the direct result of mining under deep overburden. This is, however, not necessarily true for horizontal stresses. In the eastern (and to a lesser degree the western) U.S. coalfields, an elevated horizontal stress field, produced by residual tectonic processes, has locked geologic discontinuities in place and elevated coal pillar confinement at even shallow overburdens. In some instances, the smallest adjustment to this stress field can lower shear resistance along these inherent planes of weakness, thereby releasing confinement to the coal pillar or shearing resistance to a fault plane and causing a sudden release of energy.

Clearly, an analysis of the effect of environmental factors on strata behavior is not complete without considering the effects of mining practices on exacerbated stress conditions. Holland and Thomas (1954) examined 177 coal mine bursts that occurred in the United States from 1925 to 1950 and determined that, in many instances, bursts could be averted by avoiding unfavorable mining configurations. Unfavorable mining practices contributed to bursts by creating areas of stress concentration within a mine structure.

In summary, coal pillar yielding and failure may be readily observed underground at almost any full-extraction mining section. Usually, this process proceeds in an orderly manner. Environmental factors, including geology, stress state, and mining system, can interact to effect a violent failure of coal through one of several mechanisms. Categorizing coal mine bursts by mechanism provides a framework for the development of more appropriate mine designs and, if necessary, remediation techniques. With this in mind, the following discussion will describe three categories of bursts based on mechanism: (1) excessive pressure, (2) seismic shock, and (3) loss of confinement. Additionally, remediation procedures are reviewed in light of their potential effect on these mechanisms.

Excessive Pressure Mechanism

The first coal mine burst category is defined by the excessive pressure mechanism. This mechanism has been discussed extensively by Holland and Thomas (1954). When excessive loads are applied to mine structures, mainly in the form of large abutment pressures, bursts may result. Coal pillars and barriers can be concentrators of load owing to a host of conditions. For example, if a pillar is adjacent to the gob, the combination of considerable rib crushing and abutment loading can produce high stresses in a confined pillar core (figure 3a). Commonly, massive strata exist in the immediate mine roof overlying burst-prone coal, which can cantilever, adding load to the pillar. When massive load shifts occur rapidly, the pillar's ultimate load-bearing capacity can be exceeded before the coal can shed the load in a controlled manner. Such rapid loading can be caused by a swift removal of adjacent pillars or by bursting of adjacent pillars. This mechanism can be likened to the behavior of a typical rock or coal specimen compressed to failure in a

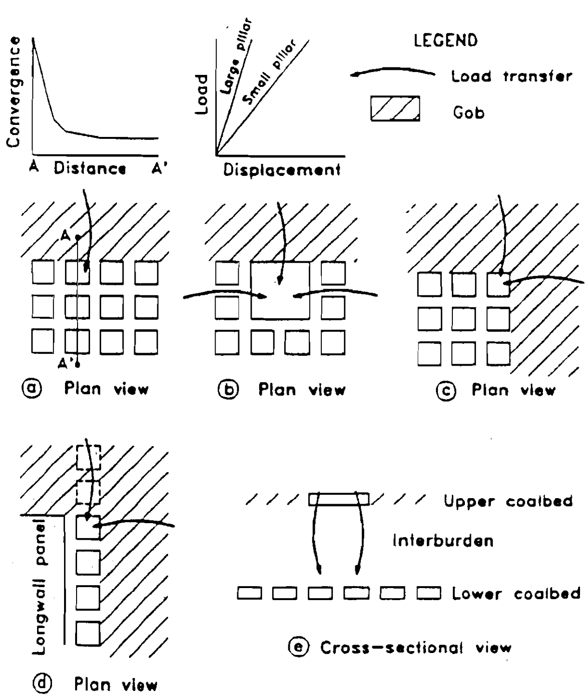

Figure 3.—Load transfer pattern found in mining sections where excessive pressure bursts occur.

testing machine whose postfailure stiffness is less than that of the rock. At the point of failure, the energy stored via the extension of the testing machine acts to drive the rock sample to fail violently. One surmises that such a situation could occur in the field as well if a similar relationship arose between the local mine stiffness and the stiffness of coal pillars, panels, or working faces.

Other mining geometries, such as a large coal pillar surrounded by smaller pillars, can concentrate stress (figure 3b). Large pillars can be imagined as stiff structures that tend to deform or converge less than smaller, less stiff pillars. These larger structures will tend to gather load, increasing the potential for violent failure as pillar extraction occurs within and around them. In addition to individual pillar geometries, section-wide mine plans and extraction sequences can contribute to coal mine bursts. For example, overlapping abutment pressures from converging gob lines (figures 3c and 3d) and overlying large pillars or barriers in multiple-seam mining operations can cause excessive pressure conditions (figure 3e). Fortunately, all of the preceding conditions lend themselves to engineering solutions.

Environmental characteristics associated with excessive pressure bursts include-

(1) Geology.–Stiff and massive roof and floor strata should persist over wide mining areas. This type of strata is generally comprised of thick sandstone occurring immediately above and below the coalbed. Faulting or intense jointing should not occur. Internal geologic discontinuities, such as large trough beds, should be minimal.

(2) Stress.–High overburden stress conditions are generally required. Typically, coal mine bursts are not experienced at overburdens less than 200 m.

(3) Mining.–Critical coal pillars are located either near full-extraction mining zones or aligned with a barrier pillar in a superjacent or subjacent mine.

A promising development in recent U.S. experience has been the refinement of geologic models predicting the locations of excessive pressure coal mine bursts. A combination of in-mine mapping, exploration drillhole data, topographic information, and mine plans can provide the necessary data to evaluate burst potential. Computer-based geologic information systems provide a means of evaluating interactions among factors that contribute to bursts and thus provide insight into the relative burst hazard (Sames and Zelanko, 1994).

The excessive pressure mechanism lends itself to both analytical and numerical modeling. For example, boundary element codes that use nonlinear material properties and energy release rate calculations provide a new capacity to test the intuition of mine planners (Zipf, 1992). Mining can now be simulated by extracting blocks of "imaginary" coal with a computer model, allowing for the relative merits of a design to be examined without expending any actual mining effort. Heasley and Zelanko (1992) successfully previewed this technique by utilizing a boundary element code that calculates dissipated energy as a measure of coal mine burst potential. The approach is useful due to the persistence of stiff, massive geologic layers that produce the characteristic cantilevered spans so often found with excessive pressure bursts. Unfortunately, there are uncertainties associated with even these rock masses, which reduce the capability to predict bursts at acceptable levels. Minor changes to material properties input to the codes tend to have considerable influence over output results. Close attention must be paid to calibrating the models with known conditions.

Seismic Shock Mechanism

The second coal mine burst category consists of a wide grouping of mechanisms associated with coal pillars subjected to seismic shocks. The seismic shock burst mechanism was first introduced by Rice (1935) in the late 1920's. Rice indicated that shock bursts stemmed from the failure of thick, massive, rigid strata

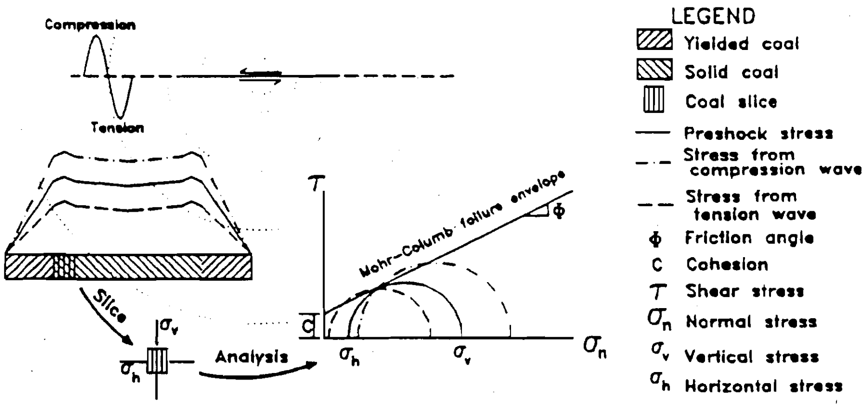

Figure 4.—Failure mechanism associated with seismic shock.

Mine	State	Richter magnitude	Date of seismic event
Jim Walter Resources No. 4	Alabama	3.6	07 May 1986.
Virginia Pocahontas No. 3	Virginia	3.0	04 March 1987.
Buchanan No. 1	Virginia	4.0	14 April 1988.
Lynch No. 37	Kentucky	2.3	22 November 1989.
Cottonwood	Utah	3.0	15 March 1991.
Soldier Canyon	Utah	3.6	21 January 1993.

Table 1.—U.S. mining-induced seismic events since 1986.

above the coalbed, which transmit a seismic shock wave to the coal below. He also stated that seismic shocks could be generated from the sudden failure of strata spanning a gob area or from the impact of a massive volume of rock onto the mine floor. Both of these mechanisms could theoretically produce a sizable shock wave, traveling through the intervening strata and affecting a wide areal distribution of coal pillars.

Investigations in Canadian deep hard rock mines have shown that rock bursts are often associated with slip along preexisting geologic discontinuities adjacent to the mine openings (Morrison and MacDonald, 1990). Stick-slip movements on these discontinuities produce a sharp, instantaneous acceleration within the strata around the mine structure. Seismic waves propagate through the mine, compressing then extending the coal pillars. This causes an instantaneous increase in load, resulting in a potentially unstable stress state (figure 4). During the next instant, load is removed, lowering confinement and potentially initiating an unstable state.

Clearly, the level of mining-induced seismic activity coming from U.S. coalfields suggests that "earthquakelike" sources may indeed be partially responsible for coal pillar damage underground. Since 1986, seismic events have been recorded from numerous mining sites, producing Richter magnitudes from 2.3 to 4.0 (table 1). Sources were associated with longwall and pillar retreat mines in Alabama, Kentucky, Virginia, and Utah. Evidence at one of these sites suggests that the seismic source occurred over 30 m above the mine opening and may have been associated with slip between large blocks of strata into adjacent gob areas.

Environmental conditions associated with seismic shock mechanisms include–

(1) Geology.–Typically stiff sandstones and siltstones with large-scale structures such as faults, persistent discontinuities like trough beds, bedding plane and slips, or repeated systems of through-going fractures within tens of meters of the mine structure.

(2) Stress.–Highly biaxial stress conditions, like those found adjacent to full-extraction zones, are generally required. When one plane of stress is reduced in the direction of the gob, slip along planes of weakness is more easily initiated.

(3) Mining.–The mining-induced seismicity may be caused by strata shifting toward full-extraction zones or may result from entries driving into unmined areas where large-scale faulting is present.

Unfortunately, temporal prediction at levels acceptable to the mining community has proved to be elusive. Problems with realizing reliable coal burst precursors continue to plague this effort. However, many new advancements have been achieved in microseismic monitoring, such as real-time display of coal mine burst locations, three-dimensional sensor installations, and underground access of data near active mining locations. These developments have made microseismic information more accessible to mine personnel so that excessive energy release locations can be related quickly to activity observed underground (Coughlin and Wilson, 1993).

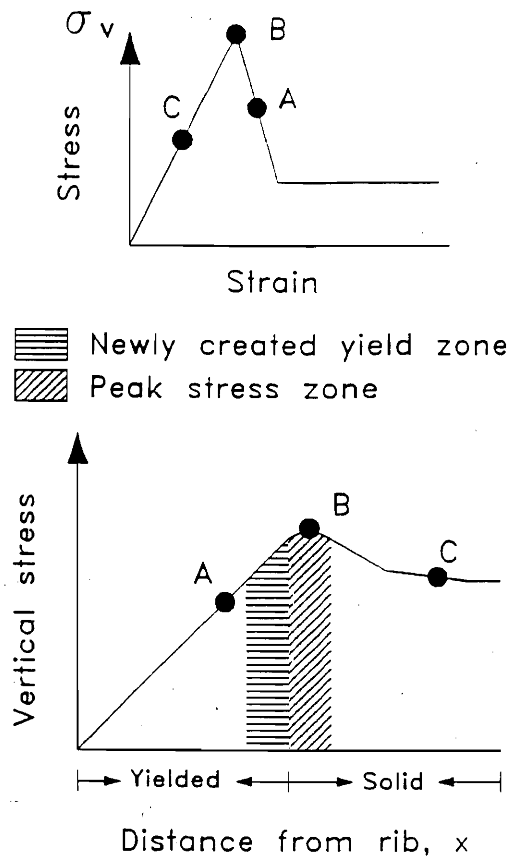

Figure 5.—Generalized vertical stress distribution within a coal pillar.

Loss of Confinement Mechanism

The third coal mine burst category is defined by the loss of confinement mechanism. Babcock and Bickel (1984) first suggested this mechanism based primarily upon laboratory investigations. By dramatically reducing the confinement (σ_3) while maintaining the vertical stress state (σ_1) within a load frame, violent failure was produced in 15 different coal materials. They postulated that if this process occurred very rapidly within a coal pillar, dynamic failure could result. Although their theory was somewhat simplistic, it showed that interface or contact interaction between the coal cubes and the steel platens of the load frame controlled the failure mode.

Loaded coal pillars are comprised of two basic parts: an elastic solid core and an inelastic yielded rib. The formation of the yield zone and its role in confining the core have been analyzed by many researchers (Barron, 1984; Salamon, 1992; Wagner, 1974; Wilson, 1973). In general, the yield zone develops inward as the edge of the solid coal zone fails. At this time, the peak stress state drops to some residual strength level, transferring a portion of the load to solid coal farther inside the pillar (figure 5). This newly fractured slice of coal receives confinement from the adjacent yielded coal and, in turn, provides confinement to the rest of the solid coal. A new peak stress zone is now located farther inside the pillar at the boundary between the yield zone and the slightly reduced solid coal zone. Additional confinement can be given to the coal from the adjacent mine roof and floor strata. The amount of confinement depends on the contact or interface characteristics (Iannacchione, 1990).

In most U.S. coalbeds, the contact between the coal and adjacent shale, siltstone, or sandstone is generally sharp. Gradational or irregular contacts are less common and mainly exist where a stiff sandstone member is in contact with the coalbed. Sharp contacts typically exhibit shear strength properties, which are less than those of coal, whereas gradational contacts assume the characteristics of the coal.

Planar discontinuities and slickensided surfaces characteristic of sharp contacts provide little resistance to shear displacements. However, in burst-prone ground, a gradational or irregular contact increases the frictional resistance at the roof and floor interfaces with the coalbed, allowing the coal to achieve extremely high peak stresses. The normal growth of the yield zone is slowed by the additional confinement from the contact zone. Movements within the contact zone occur in a stick-slip fashion. When slip occurs, the elevated stress conditions are finally overcome. A rapid release of shearing resistance triggers movement and a massive loss of confinement for the rib coal and the adjacent peak stress zone within the solid core (figure 6).

Environmental conditions that are important in contributing to the loss of confinement mechanism include–

(1) Geology.–The contact zone between the coalbed and surrounding strata, usually a stiff sandstone, is generally either gradational or rough and irregular if it is a sharp contact. This can be a very localized condition, such as a sandstone channel scour that penetrates portions of the coalbed.

(2) Stress.–In general, high in situ stresses are needed. These can be supplied by a high residual horizontal stress field, excessive overburden pressure, or abutment pressures from full-extraction mining.

(3) Mining.–Bursts generally occur at the working face of the mine in association with coal extraction. They can therefore occur over a wide range of mining operations, including entry development, longwall extraction, and pillar recovery.

Because this mechanism is very sensitive to small changes in geology, considerable attention should be placed on observing the conditions of the yielded coal. The depth and character of the fractured coal zone

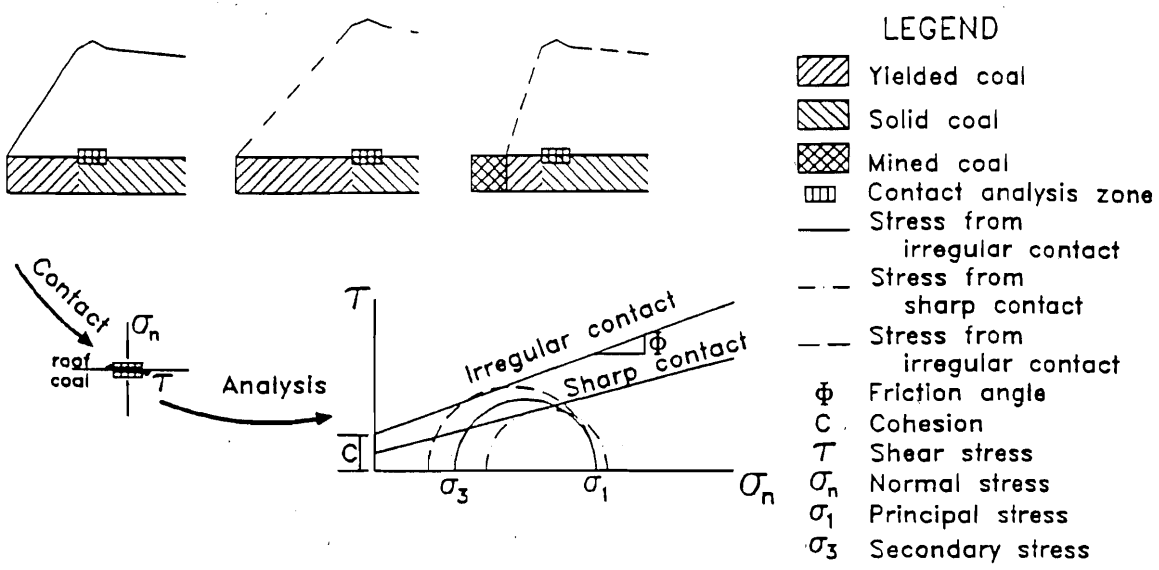

Figure 6.—Failure mechanism associated with loss of confinement.

reveals the position of magnitude of the peak stress zone and, therefore, the potential for violent failure. Numerous techniques are available to acquire this information, including both observational and instrument-based procedures. If the ribs are generally crushed, but locally appear straight and solid, this may indicate that the peak stress zone is close to the coal pillar edge. If the ribs are difficult to cut or drill, this may indicate an abnormally high peak stress zone. The presence of a sandstone channel scour may signal the change in the character of the contact zone. The irregularity of the scours generally provides higher shearing resistance.

The appearance of a dusting of "red coal" at the contact zone is perhaps the most dramatic indicator of the imminence of a coal mine burst. This condition indicates the coalbed's inability of resist shearing forces generated by the tremendous confinement locally applied to the coal. The red coal zone probably represents coal that has been mechanically altered due to the presence of excessive amounts of shear strain. U.S. Bureau of Mines researchers have observed this condition at three different burst-prone mines: the Olga and Gary No. 2 Mines in southern West Virginia and the Lynch No. 37 Mine in eastern Kentucky.

Auger drilling also has been used as a technique to probe for areas of highly stressed coal. Often, after a particular mining face has burst, small-diameter (5-cm) auger holes are drilled into the face with handheld units. Drillhole cuttings are often monitored, but generally the mining company is most interested in determining when drilling difficulty or drill string seizures occur. At these points, it is assumed that the drillhole has entered an area of high stress. A number of holes are drilled across the problem working face at distances of 2 to 6 m. If the peak stress zone (figure 5) is close to the entry (less than 2 m), the situation is generally deemed critical and mining temporarily ceases or some destressing technique is attempted. If the peak stress zone is greater than 5 m from the entry, conditions are generally considered safe for additional mining at the face. It should be noted that no reliable criteria exist to guide the mining company in determining how often a face should be probed or in selecting drilling parameters or patterns. Longwall mines such as Dutch Creek in Colorado and Lynch No. 37 in eastern Kentucky have utilized this technique to predict the location of destressing.

REMEDIATION TECHNIQUES

A summary of useful designs to reduce the severity and occurrence of coal mine bursts has been presented by Iannacchione and DeMarco (1992). In room-and-pillar mining, the use of straight retreating coal pillar lines, small and uniform pillars, and sequential splitting of pillars can effectively move excessive stress conditions in a controlled manner away from the working face of the mine. In longwall mining, by contrast, sizing gate entry pillars either large enough to contain induced stresses or small enough to yield in a controlled way can effectively reduce bursts and their magnitude. Such design approaches should be the first line of defense against bursts, and remediation measures should be considered only as a last resort.

Auger destress drilling was first practiced at the Gary No. 2 Mine, McDowell County, West Virginia, in the mid-1950's by augering 61-cm holes from the sides of highly stressed barrier pillars (Talman and Schroder, 1958). Unfortunately, these large-diameter boreholes were prone to trigger large coal mine bursts. As a result, auger holes with diameters of less than 10 cm have been used recently, because they are believed to be incapable of initiating a burst. The augering process effectively shifts the highest stress areas away from the coal pillar edge without removing any of the confining fractured and yielded rib coal. This technique may prove most effective when the mechanism is believed to be excessive pressure or loss of confinement.

Shot firing fractures coal, thereby extending the yielded coal zone. This process injects energy into stressed coal, causing seismic shock. The shock waves temporarily release confinement, initiating violent failure under a "controlled condition." This technique could prove effective with all three categories of coal mine bursts.

Water infused into a coalbed has the potential to initiate slippage between rock surfaces, lowering the state of confinement on the surface and the energy stored within this system. This technique may prove most effective when the mechanism is believed to be excessive pressure or loss of confinement.

Several other techniques have remained untried, but should be mentioned here. In some instances, it has been difficult to achieve good caving into full-extraction gob areas. This is believed to be a function of the ability of these massive units to span over the gob. Hydraulic fracture has the potential to induce strata caving by propagating a fracture or to induce strata slip by lubricating a significant geologic discontinuity. This technique may prove most effective when the mechanism is believed to be excessive pressure or seismic shock.

SUMMARY AND CONCLUSIONS

U.S. coal mine bursts may be categorized by three distinct source mechanisms: excessive pressure, seismic shock, and loss of confinement. These mechanisms define categories with unique geologies, stress conditions, and mining scenarios. Categorizing coal bursts in this manner allows spatial prediction and establishes rules by which control measures and remediation efforts may be selected.

In general, coal mine bursts caused by excessive pressure occur in massive strata comprised mainly of sandstone, free of persistent geologic discontinuities. Stresses are generated from a combination of overburden and abutment loads resulting from mining adjacent to full-extraction zones. This type of burst lends itself to empirical, analytical, and numerical design procedures and is often a result of faulty mine plans. Therefore, spatial prediction is possible, and engineering designs and control techniques are available to mitigate this category of bursts.

Coal mine bursts caused by seismic shock occur in stiff strata with large-scale discontinuities that afford movement, principally into gob zones. Stresses are biaxial, which can assist in fault-slip-type movement. A wide variety of mining scenarios can be associated with this category. In general, microseismic monitoring techniques are useful in locating zones of seismicity. Once the nature of the seismicity is understood, engineering design and control techniques similar to those used for the excessive pressure category can lower the overall stress states on a section-wide basis. This would lower the ability of a seismic wave to initiate structural damage. Shot firing techniques allow for the reproduction of seismic shock effects under controlled situations. Hopefully, additional options, such as prefracturing strata to induce controlled movement, can be developed in the future.

Finally, coal mine bursts caused by loss of confinement occur where the contact between coal and mine roof or floor resists movement. These zones can be very localized and are generally associated with sandstone channel scours. The peak stress zone is generally found exceptionally close to the coal rib. Bursts occur in direct response to mining within the yielded coal adjacent to the peak stress zone. This type of burst can occur during coal pillaring, working face development, or panel extraction. Burst potential is best identified with drilling, but can also be recognized with rock mechanics instrumentation. Mitigation measures are limited to destressing techniques, including the use of water infusion to lower coal confinement.

The above model is provided with the hope that a logical, effective methodology can be recognized that will allow for the rapid execution of the most efficient coal mine burst control technique.

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