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Roof Control Strategies for Undergound Coal Mines

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	lb	pound (force)
in	inch	lb/ft^3	pound (force) per cubic foot
in/ton	inch per ton		

ROOF CONTROL STRATEGIES FOR UNDERGROUND COAL MINES

By William C. Smith[1]

ABSTRACT

Roof support, an important aspect of ground control, involves maintaining roof competency to ensure a safe and efficient mining environment. Wide variability in rock quality and stress distributions requires a systematic approach to roof support design that satisfies specific goals. The success of past roof support in reducing the incidence of roof falls has been primarily attributed to safer roof bolting practices. However, roof falls continue to be the number one occupational hazard in underground coal mines.

This U.S. Bureau of Mines report presents a general overview of roof bolting and other roof support methods used in the United States. Characteristics of bad roof and associated roof failure theories are briefly presented as background to roof support. Methods of detecting and monitoring roof behavior and/or bolt performance provide essential feedback on roof support requirements. A discussion follows on roof bolt design that assimilates roof and support parameters into useful equations or nomographs to help decide what bolt types to use and how they should be installed under different roof conditions.

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INTRODUCTION

The potential for roof rock instability is a function of stress field distributions, rock properties, and/or geologic structure of the immediate roof. Poorly defined data on such parameters may often distort the identification or prediction of unstable roof conditions. While rock properties and geologic structure remain relatively constant in a given area during the life of a mine, the stress field does not. Fluctuations in the magnitudes and locations of the stress field, in combination with weak roof rock in terms of physical properties and geologic structure, produce conditions conducive to mine roof instability. Induced stress field changes are usually mine related and can be caused by alterations to mine layouts, extraction sequences, and mining rates. Local changes in geology also affect roof behavior because of changes in the stress field.

Roof rock failure is alleviated in one of two ways:

1. Reduction of magnitudes and/or changes in direction of the stress field, or
2. Application of roof support to maintain roof stability.

This paper will focus on roof support, primarily roof bolting.

The U.S. Bureau of Mines has advocated the use of suspension roof support or rock reinforcement in coal mines since the early 1940's as an effective method to reduce the number of roof-fall accidents. The roof bolting concept was proposed in 1943 by Weigel as a systematic procedure, as illustrated in figure 1, to support weak roof (*1*).[2] Weigel established several important guidelines for bolting:

1. Support weakened rock that falls below the natural arch line;
2. Bolt early in the mining cycle; and
3. Bolt weak, thin strata together to create thicker, stronger strata.

These guidelines remain valid today.

Currently, with a few exceptions, operating underground coal mines in the United States are using roof bolts for primary and/or secondary support. Even so, from 1980 to 1990 there were 298 fatalities and over 7,100 nonfatal days lost due to roof falls in U.S. underground coal mines (*2*). The purpose of this report is to examine the practice of roof bolting and other roof support as well as methods for developing effective roof support strategy for underground coal mines.

[2]Italic numbers in parentheses refer to items in the list of references at the end of this report.

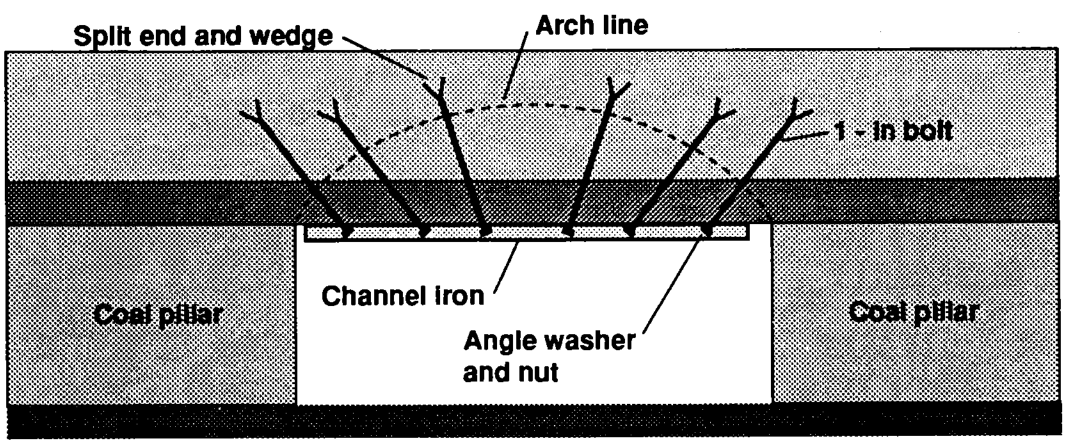

Figure 1.—Roof bolting strategy as proposed by Weigel (*1*).

ROOF BOLTING

OVERVIEW

While there are many other kinds of bolt designs, four basic bolt types are dominant in U.S. underground coal mines: the mechanical bolt, which is anchored at one end with an expansion shell; the point resin-anchored bolt, which uses a short resin column; the combination bolt, which is similar to the point resin-anchored bolt, but has a longer resin column (greater than 24 in); and the fully grouted bolt.

The bolt steel for all bolt types is manufactured in accordance with specified American Society for Testing and Materials (ASTM) minimum requirements relating to yield strength, ultimate or tensile strength, and percent elongation (*3*). This information is useful when selecting bolt systems with specific characteristics to accommodate certain roof conditions, such as applying bolt tension and/or resisting high roof loading. Other characteristics important to bolt steel are length and diameter.

Generally with point-anchored bolts (includes mechanical, point resin-anchored, and combination bolts), pretensioning is applied by torquing the bolt a predetermined amount, which, in theory, corresponds to a given tension load. A general rule-of-thumb estimate of the torque-to-load ratio is usually 40 to 50 lb of load for each foot-pound of torque, depending on the yield characteristics of the bolt. Other factors that can influence the torque-to-load ratio include variations in bolt thrust and the amount of friction due to the condition of the bolt threads. Another drawback of using torque-tensioned bolts in soft rock is maintenance—the need to regularly retension bolts. Assuming the bolt hardware is installed and functions properly, tension bleed-off can be expected to occur most likely in weak, incompetent rock strata that are highly fractured or easily squeezed. Alternative supports, such as fully or partially grouted bolts (point anchor), offer greater safety and performance under adverse roof conditions.

The fully grouted bolt is installed in a borehole with a full-length column of resin grout. This bolt type is more effective than most point-anchor bolts in weak, highly laminated shales and other soft rocks, with or without tension applied.[3] Untensioned full-length grouted bolts have gained wide acceptance in many U.S. underground coal mines and have worked well in most cases. Tensioned, full-length resin-grouted bolts provide the advantages of a tensioned and fully grouted bolt in two ways: Tensioning the bolt resists initial roof sag, and using a full length of grout helps establish good beam-building characteristics. Pretensioning fully grouted resin bolts involves directly applying an upward force of 1 to 4 tons during bolt installation. This requires a bolter with sufficient thrust capability. The technique, which has been practiced in Europe and Australia (*4*) for many years, is currently being studied by the Bureau and is quickly gaining acceptance in U.S. coal mines (*5*). Another method of pretensioning a fully grouted bolt that is practiced in western U.S. coal mines involves using a two-stage fully grouted system in which the first-stage resin sets initially, allowing the installer to torque the bolt before the second-stage resin hardens.

All grouted bolts rely significantly on the integrity of the grout and rock interface. Research has been conducted to explain this interaction in detail (*6-7*). Calculated anchorage capacity (based on unit anchorage times grouted length) of most resin-grouted bolts exceeds the yield strength of the rebar when the bolts are loaded longitudinally. Other research has shown that a minimum grout column length of 24 in sufficiently anchors most properly installed bolts in coal-bearing strata (*8*). The benefits of using fully grouted bolts include high resistance to shear forces, good beam-building characteristics, and improved keying effect.

ANCHORAGE FAILURE

Anchorage failure, the most common type of rock bolt failure, renders rock bolts less effective in applying support to a rock mass. Usually anchorage difficulties are more prevalent in soft rock, such as coal and shale, than in hard rock.

Loss of anchorage occurs as a result of damage to the surrounding rock or damage to the anchor itself. Anchorage failure in tensioned roof bolts results in loss of tension in the bolt and a subsequent drop in compression and confinement of the rock strata between the bolt ends, causing a loss in both beam-building and suspension effects. Anchorage failure in untensioned resin bolts results in diminished beam-building effect, reduced load-carrying

[3]This is true when a stiff bolting system is required. In exceptionally plastic-type rocks where high loading may be expected, more yieldable bolting systems may be needed.

capacity attributed to a lower suspension effect, and decreased shear resistance to horizontal stress. Anchorage ineffectiveness, in any case, may increase rock relaxation around the bolt and eventually trigger failure of the immediate roof.

Causes of poor anchorage are generally improper installation practices. With mechanical bolts this may be caused by improperly torquing bolts or using the wrong size or type of anchor for a given rock type. With untensioned resin-grouted bolts poor installation practices include oversizing bolt holes and not following manufacturers' recommended spinning rates and times.

Pull tests should be conducted routinely to check if proper installation procedures have been undertaken. Torque testing can be used to test anchorage in mechanical bolts. Anchorage capacities of rock bolts can vary widely in different kinds of rock and even in the same rock type (*8-9*). Fracturing associated with bolt anchorage in soft rock has been characterized as two possible types:

1. Crushing of the host rock, which occurs along the bolt periphery; and
2. Cone-shaped fracturing, which radiates from the anchor into the host rock (*10*).

Shear deformation in the rock surrounding the bolt can have a dramatic effect on bolt integrity. Tensioning bolts can significantly alter the shearing resistance along a "free-sliding" discontinuity, depending on the magnitude of the average normal stress that is present. In ungrouted tensioned bolts, loss of tension affects overall bolt effectiveness by decreasing shear resistance when shear deformation is present. Fairhurst has shown that fully grouted bolts increase shear resistance for each layer of rock and have little carry-over effect to adjacent bolts when a single grouted bolt fails (*11*). For this reason, researchers advocate using fully grouted bolts when a significant degree of shear deformation is expected in the roof rock.

BOLT LENGTH AND SPACING

Generally, bolt length is based on the height of unstable roof, or in other words, the depth in the roof to the first major weakness plane, such as a clay stringer or rider seam. The only practical limit to bolt length is the roof-to-floor height of the opening. For instance, a 4-ft-high opening can accommodate up to a 4-ft-long bolt, or a slightly longer bolt if bendable bolts are used. If roof bolts are to act mainly in suspension, then the important criterion is that the bolts be long enough to be firmly anchored in a competent rock layer. According to mining regulation, if mechanical bolts are used, at least 1 ft of the bolt must be anchored in competent strata. If a suspension effect is not desired, resin-grouted bolts need to be long enough to promote the friction effect that encourages beam-building. When it is unclear as to whether to design support for a suspension or friction effect, it is generally better to design for both and then use the more conservative approach. In many coal mines, 4- and 6-ft-long bolts will suffice.

In the United States, Federal regulation CFR 30 requires that coal mines follow a systematic pattern of bolting, e.g., 4-ft by 4-ft or 5-ft by 5-ft spacing, regardless of bolt length (*12*). This usually translates into a length-to-spacing ratio of 1.0 or greater. Because bolt pattern and strata interact, factors that may affect optimum bolt spacing are strata thickness, location of weakness planes, rock type and quality, bolt tension, and other bolt characteristics, such as yield strength, length, and diameter.

Fairhurst and Singh have pointed out that following a prescribed systematic bolting pattern will not work for every situation (*11*). Sometimes the engineered bolting system patterns work too well by leaving the supported rock intact, resulting in an entire section of supported roof collapsing as a unit. Thomas (*13*) and Jorstad (*14*) have observed this type of artificial fracturing passing through the ends of the deepest bolts. The research showed that the fracturing is more likely to propagate as bolt spacing is reduced. Generally, the creation of additional fracturing in the roof rock is insignificant when compared to the additional reinforcement provided by the bolting system. In special cases, it can be debated whether the disturbance in the roof rock was caused by the extra bolts or unusually high shear forces already present in the roof rock requiring the denser bolt pattern—probably, it is a combination of both. Regardless of the actual cause, induced fracturing, combined with high abutment stresses due to mining, may constitute a dangerous roof condition that deserves attention.

Varying the length and placement of individual bolts (fig. 2) can reduce the likelihood of severe horizontal roof delamination (*15*). Staggering bolt lengths by using longer bolts in the center of the entry is sometimes effective when rider or weak clay seams are present. Angle bolting, either to the inside or outside of the opening, as shown in figure 2, can be usefully applied in combination with regular bolting. Extra-long bolts, up to 20 ft long, are sometimes used to reduce cutter roof conditions.

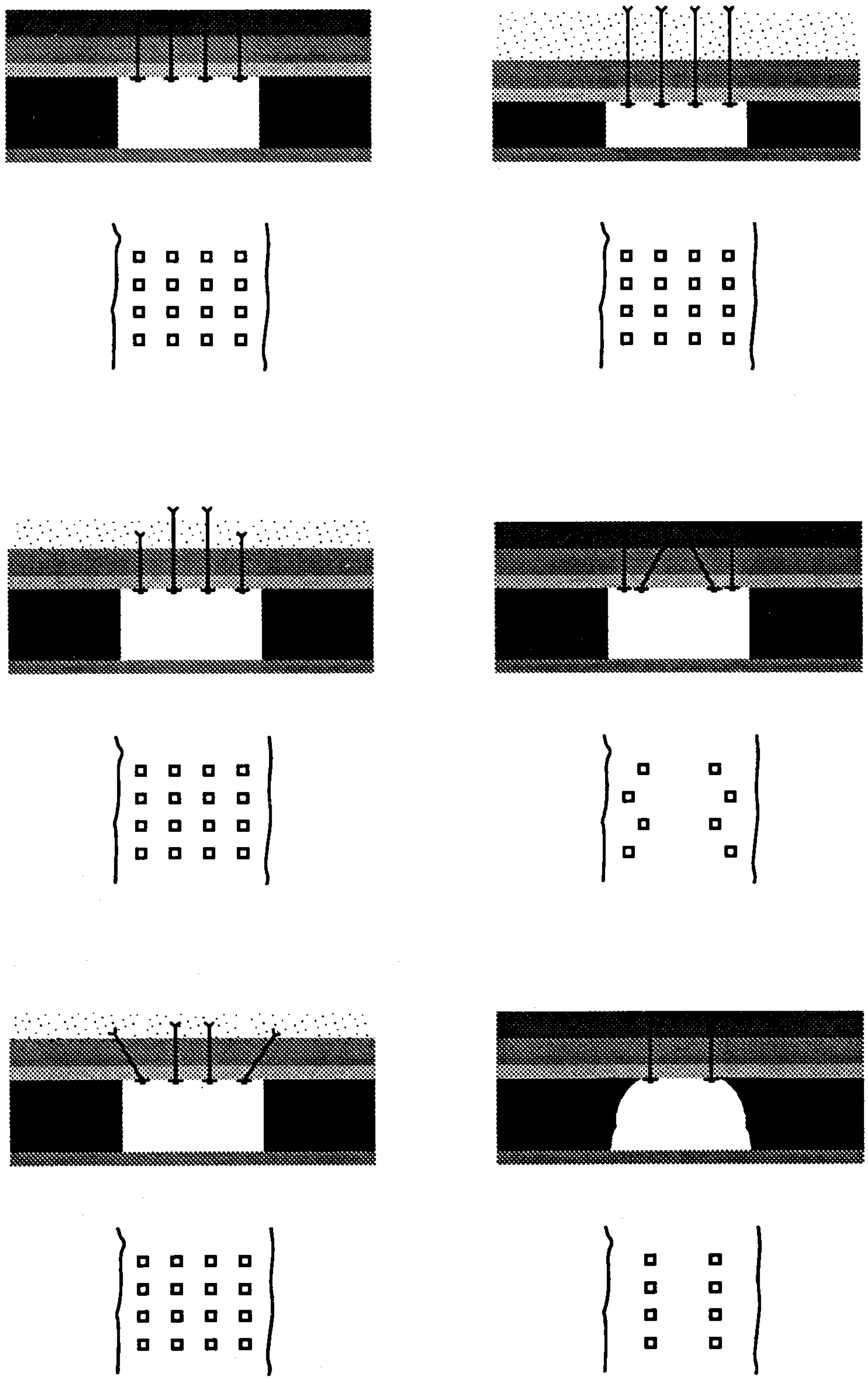

Figure 2.—Different strategies for installing roof bolts (15).

ROOF FAILURE: CAUSES AND CONTROL

Increasing stress levels above a mine opening may lead to a catastrophic roof condition, while controlled stress levels usually indicate improved roof stability. Parameters influencing roof stress distributions and magnitudes during mining are

1. Load-deformation behavior of the roof and rib,
2. Time-dependent behavior of the roof and rib,
3. Premining virgin state of stress,
4. Stiffness characteristics of roof, rib, and floor, and
5. Effects of cyclic and variable loading on confined and unconfined roof rock and rib coal properties.

Another important factor affecting stress distributions is the time delay experienced between mining and bolting exposed coal mine roof. The idea behind this is that timely installation of bolts reduces dilation and other destructive deformation of the roof rock. The consensus on whether this process actually occurs is mixed. A research study found that in some mines, over half of the bedding plane separations occur prior to the installation of roof bolts, accounting for much of the instability (*11*). Yet researchers at another mine found evidence to the contrary—no relationship between time delays and the resultant stress distribution (*16*). This difference in research findings may indicate that time delays have varying effects on roof stability in different mines.

A general assumption made when measuring roof displacements under supported roof is that roof movement is indicative of instability. To the contrary, considerable downward roof movement may occur in coal mines without an eventual roof fall. For example, roof movement can occur when competent roof members put downward pressure on a soft or yielding pillar. In this case, larger and/or reinforced pillars may be required. Increasing roof movement without pillar squeezing indicates a far more dangerous situation in which strata separation is occurring and high roof stress may be building. Upward floor movement (floor heave) is also often an indication of high roof stresses and, in combination with downward roof movement, contributes to convergence, reducing the effective height of the opening. For longwall coal mines, these high stresses are particularly important to entries along the abutment zones near the coal face, where induced loading is the greatest.

Increasing horizontal roof stresses may lead to buckling, particularly when the roof rock is thinly laminated, causing roof strata rock to collapse. Buckling behavior, when left uncorrected, can lead to dome-like failures. When the dome-shaped failure proceeds, the immediate roof detaches in the manner of a cantilever beam aligned in the direction of the major horizontal principal stress direction (*17*).

To prevent or reduce roof falls, adequate rock reinforcement is required using one or a combination of three methods: beam-building, keying effect, and suspension, as shown in figure 3. The recognition that roof strata are

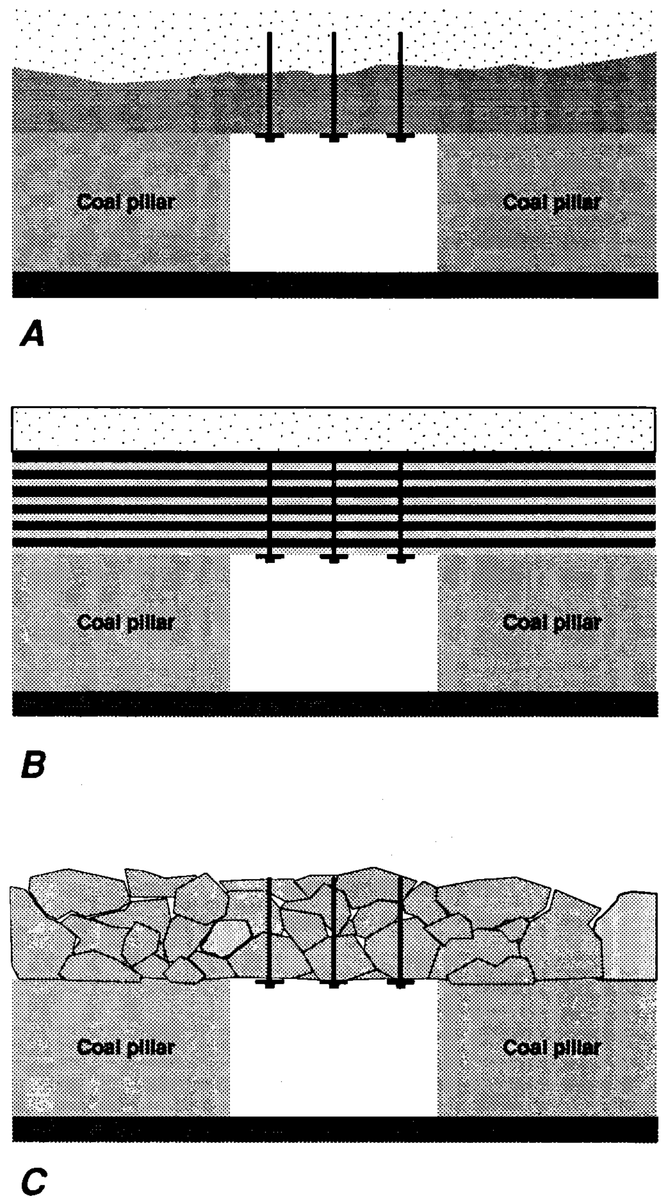

Figure 3.—Three basic roof support theories for bolting. *A*, Suspension; *B*, beam-building; *C*, keying effects.

roughly analogous to laminated beams or plates provides one explanation for how roof bolts may work in supporting weak roofs. Installation of a suitable pattern of roof bolts binds the strata between the bolt ends and increases the capacity of individual strata to resist bending moments and horizontal (compressional) forces that can lead to buckling: This is "beam-building." When the roof strata are highly fractured and blocky, bolting increases frictional forces between blocks to resist sliding and/or separation along fracture surfaces: This is keying effect. Figure 4 shows how bolts can increase the support capacity of the roof strata. Application of tension to the bolts would, theoretically, cause compression between rock layers, enhancing the shear strength between strata. Suspension effects arise when a weaker rock layer is supported by a stronger rock layer through bolting. In this case the bolts support the dead weight of the strata between the bolt head and anchor.

The reinforcement ability of bolts is primarily due to friction that exists because of the physical interlocking along the anchor and rock interface. A design chart developed by Panek (*18*), shown in figure 5, suggests that for mechanical bolts, friction can be increased by increasing bolt tension, decreasing bolt spacing, increasing the number of bolted strata beds, and/or decreasing roof span. Fully grouted untensioned bolts rely on frictional forces arising along the grout-rock contact instead of bolt torque. Combination and other tensioned grouted bolts share support characteristics of both mechanical and grouted bolts.

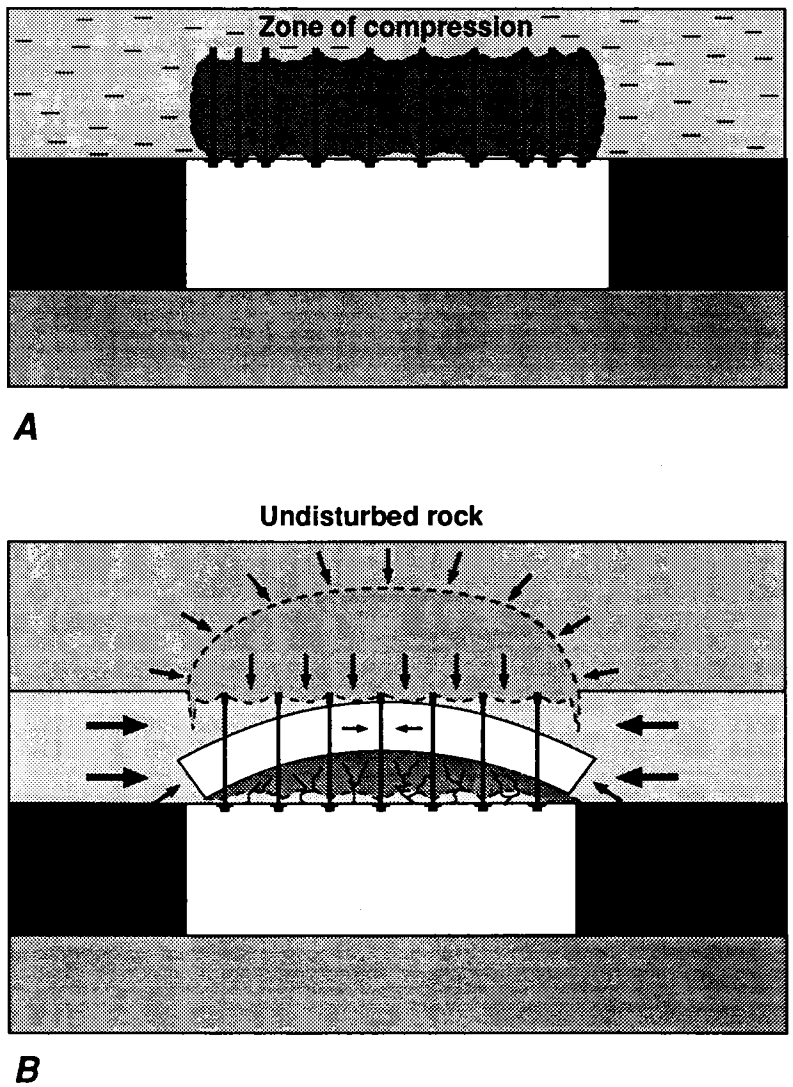

Figure 4.—Bolting can provide a support arch above opening. *A*, Compression zone; *B*, support arch.

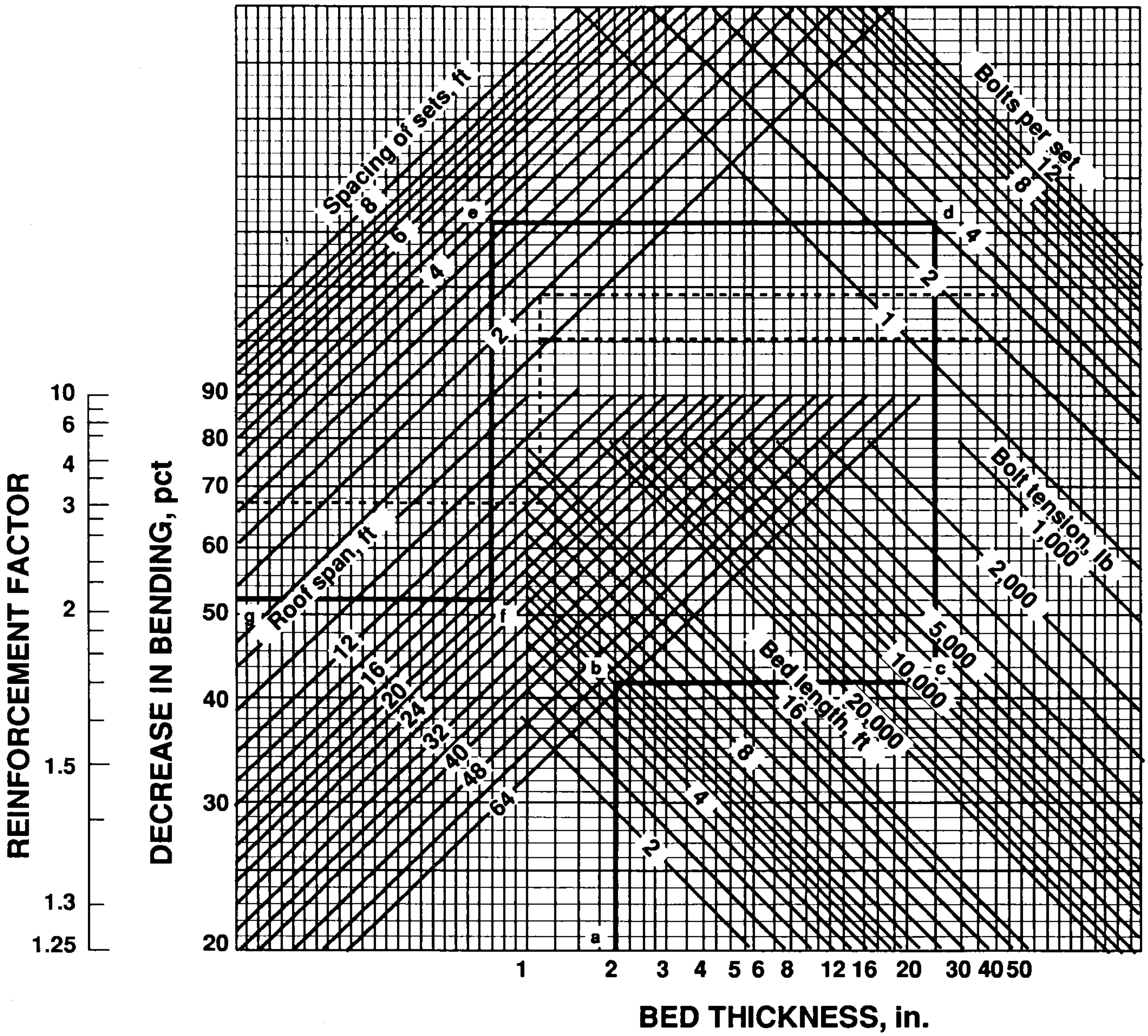

Figure 5.—Design chart for mechanical roof bolts (Panek) (*18*).

EFFECTS OF HUMIDITY ON SUPPORTED ROOF

Although humidity is not strictly a ground control-caused problem, Bureau research has identified it as the most significant climatic phenomenon influencing roof-fall occurrence under supported roof (*19*). The effect of humidity on coal roof rock had been previously substantiated in the laboratory (*20*). The results from the Bureau field study established a statistical link between humidity associated with certain seasons and roof-fall incidence. Short-term humidity effects on roof-fall occurrences have been more difficult to prove, but they should be considered in mines with unusually high moisture levels. Some research has measured greater roof sag in the spring and summer than in the rest of the year because of high humidity (*21*).

To maintain roof stability under wet conditions for indefinite periods of time, coated rebar and/or fully grouted resin bolts offer greater protection from bolt deterioration due to corrosion effects. With the exception of conditions where high water infiltration through the borehole has affected installation, grouted bolts have not been shown to be seriously affected by humidity in underground coal mines.

DESIGN PROCEDURES FOR OPTIMUM ROOF BOLT REINFORCEMENT

Several design procedures have been developed for roof bolt reinforcement. Generally, the overall procedure should relate the characteristics of the rock mass, stress conditions, and opening geometry to the predicted support requirements. Roof support design methods represent general guidelines for establishing a roof support system. Two approaches for design guides are (1) the empirically based system, which is dependent on the past history of ground control problems, and (2) the objectively based system, which is dependent on roof and rock mechanics theory to solve roof support problems. A third approach that is often used is to combine the empirical and objective approaches. Because of the uncertainty associated with trying a new support method, results from these design guides are only a starting point from which relevant support decisions are made regarding, for example, choice of bolt, grade, diameter, and spacing. Step-by-step procedures for several different support design guidelines follow.

EMPIRICAL-BASED ROOF BOLT SYSTEM DESIGN

1. Conduct an extensive and systematic long-term monitoring program.
2. Compile a list of empirical rules of support and rock mass parameters that apply for a specific or similar mine based on past experience. For example,
   a. What bolt types have been tried?
   b. What worked under what roof conditions?
   c. What "rules of thumb" have been used in support selection?
   d. What bolt dimensions and patterns work best?
   e. What are signs that bad roof is being encountered?
3. Develop a design chart or data base describing different ground conditions and support solutions that have worked in the past under similar conditions at a given or similar mine. This chart can be used to solve similar problems as they occur. Careful records should be kept of the success or failure of selected support solutions, and updates should be made as new information becomes available.

The mine or mines should have a long history of trying different support strategies for different ground conditions. Otherwise unique ground control problems may arise that require innovative solutions borrowed from other similar mine conditions. For instance, a mine that begins to experience roof falls in intersections might consider using trusses with long bolts, based on successful truss performance at other mines with similar problems.

The empirical approach relies less on engineering and rock mechanics theory than it does on systematic data input regarding past roof instability and support problems and the accompanying solutions attempted, noting the degree of success in each case. Many of the current "rules of thumb" come from empirical studies and result in a set of rules that specify bolt design guidelines regarding setting tension of mechanical bolts, bolt length and spacing, and bolt pattern. For example, to choose adequate bolt tension setting for a mechanical bolt,

1. Determine the yield strength and anchorage capacity;
2. Choose the lowest number and multiply by 60%. This is the recommended tension setting load based entirely on bolt capacity using a commonly used "rule of thumb."

A major drawback of the empirical approach is the emphasis on the roof control problem itself and the lack of attention given to the actual causes behind the instability. Circumstances may arise where a solution to a frequently occurring support problem may no longer work because of different roof conditions. For instance, major shifts in the stress field and roof geology after mining several longwall panels may require using stronger and longer roof bolts than were previously used. The following methods use more technical approaches to designing roof support.

OBJECTIVE-BASED ROOF BOLT SYSTEM DESIGN

Objective approaches generally require determination of parameters by equations or rating systems, which numerically characterize the roof rock, the support characteristics, and/or the stress conditions. One such approach uses Lang-Bischoff's Reinforced Rock Unit (RRU) concept to calculate the minimum setting tension for mechanical bolts.

Lang and Bischoff's RRU Concept (*22*)

1. Find the minimum bolt tension, T, that will satisfy the "limit equilibrium" of the RRU, with the following equation:

$$T = \alpha \frac{\gamma AR}{k\mu} \left(1 - \frac{c}{\gamma R} - \frac{h\mu}{\gamma R}\right) \frac{1-e^{-k\mu D/R}}{1-e^{-k\mu l/R}}, \quad (1)$$

where T = minimum bolt tension,

α = ratio depending on time of installation of bolts after excavation (0.5 for active reinforcement and 1.0 for passive reinforcement),

γ = unit weight of the rock,

μ = tan ϕ, where ϕ is friction angle of the rock mass,

c = apparent cohesion of the rock mass,

k = $(1 - \sin \phi)/(1 + \sin \phi)$,

h = average horizontal stress,

l = bolt length,

A = reinforced area ($s \times s$, where s = bolt spacing),

R = shear radius of rock column (s/4),

and D = height of stressed rock above opening (l + s).

2. Solving for T will give the minimum bolt tension (lb) that is needed to ensure stability of the roof strata (based on beam theory and assuming competent strata with full load transfer).

Note: One major drawback to this method is that the geology and rock condition (other than friction angle and cohesion) are not considered. For most instances, roof rock is at least moderately competent in that it generally remains intact using conventional bolting practices. However, in exceptionally weak rock, the procedure underestimates T.

Another objective approach to support design is Panek's roof bolt design chart that considers the interaction of many roof and roof-support-related factors to compute the Reinforcement Factor (RF) of the bolted roof system.

Panek's Friction Effect Design Chart for Mechanical Bolts (*18*)

1. Inspect roof falls to determine height and width of the failure in a test area (if possible). Otherwise, use core logs or a borehole penetrometer (*23*) to locate competent strata and potential failure zones.

2. Conduct pull tests to determine anchorage in rock strata above the roof-fall line.

3. Choose an acceptable installed bolt tension.

4. Choose trial values for bolt spacing ranging from 3 to 5 ft, a range strictly specified in most roof control plans. Lang determined that the bolt length-to-spacing ratio should range between 1.2 and 1.5 for coal mines (*22*).

5. Use Panek's design chart, as shown in figure 5, to calculate an RF.

6. Conduct trial bolting installations using arbitrarily chosen RF's. Try different bolt parameters (using Panek's design chart) with higher RF's for improved bolt performance.

An example of how this can work is shown in figure 5 by following the path construction from right to left as depicted by points *abcdefg*. Beginning with bed thickness *a* and moving horizontally and vertically from point to point, select bolt length *b*, bolt tension *c*, the number of bolts per set *d*, the spacing of sets *e*, the roof span *f*, and, finally, determine how much to limit bending in the roof beam and the associated RF factor by moving horizontally across to the y-axis. In the example, for a roof with 2-in average bed thicknesses and 20-ft wide openings, using 5-ft bolts tensioned to 8,000 lb with three bolts per row and 4 ft between rows reduces strata bending by at least 52% and represents an RF of slightly greater than 2.0.

Changing any parameter in the chart will result in a different RF. Often an RF ranging between 2 and 3 is adequate for many coal mines. For greater stability, Newman (*24*) reports that RF's of 3 or greater represent average roof stand-up times ranging from several months to over 5 years.

ROCK MASS CHARACTERIZATION FOR ROOF SUPPORT DESIGN

Many roof support approaches, such as Lang-Bischoff and Panek's design chart, avoid any detailed characterization of the roof rock in coal mines. One reason for this is the lack of standardization and understanding of what parameters should be used to gauge rock quality in situ. Laboratory-derived values for physical strength properties involve small rock samples that seldom are representative of the overall rock mass, largely due to improper sampling procedures and little-understood scaling relationships. However, some form of objective rock characterization method is needed to evaluate the roof rock and support interactions more fully.

The Geomechanics Rock Classification System, developed by Bieniawski (*25*), offers a procedure that more accurately assesses roof rock competency. The method determines rock mass quality by combining key parameters, such as uniaxial compressive strength; rock quality designation (RQD), also known as percent drill core recovery; and joint spacing, orientation, and condition.

Newman (*24*) suggests that modifications to the basic rock mass rating system (RMR) are required to adapt the method to coal-measure rocks; he recommends adjusting for horizontal stress, anomalous geologic conditions, and roof reinforcement to account for anomalous conditions when bolt loads may be significantly higher than normally expected (unusually high loading conditions would result in significantly lower RMR values). The range in rock quality under RMR is as follows: 80 to 90 is very good, 60 to 70 is good, 40 to 50 is fair, and 20 to 30 is poor. Obtaining the RMR for a particular roof rock is useful for determining the rock load height (roof arch) above the opening and for calculating the actual volume of rock responsible for loading the roof bolts under most conditions.

DESIGN FOR RESIN-GROUTED BOLT SYSTEMS USING BOTH APPROACHES

A third approach to designing roof support is to use a combination of empirical information with an objective analysis of support and geologic conditions. For example, the following procedure, which establishes design guidelines for resin-grouted bolting systems, allows for input of empirical information such as the average roof-fall height in lieu of calculating the roof load height using RMR. Generally, choosing the more conservative value, in terms of safety, is a valid approach for selecting appropriate parameters. The procedure shown below calculates an RF factor to help gauge roof stability (*25*).

1. Determine the bond factor (BF) based on Gerdeen (*26*) using rock type or compressive strength.
2. Determine host strata density and thickness, roof dimensions, and bolt layout.
3. Calculate rock load height (H_t) using one of two methods:
   a. $H_t = [(100 - RMR)/100] \cdot W$, where RMR is the rock mass rating in accordance with Geomechanics Rock Classification System and W is the roof width.
   b. H_t = estimated roof-fall height. This can be obtained from observed roof-fall trends.
4. Calculate bolt length, L (choose greatest): $L = H_t/2$; or $L = W/3$.
5. Determine bolt capacity, BC (choose lowest): $BC = L/BF$; or BC = yield strength.
6. Calculate bolt load, BL: $BL = (G \cdot T \cdot W \cdot RL)/[(NBR+1) \cdot (NBPR+1)]$, where G is roof rock density, T is roof rock thickness, RL is roof length, NBR is number of bolts rows, and NBPR is the number of bolts per row.
7. Determine RF using the ratio BC/BL.
8. Evaluate RF; improve RF by reducing spacing or using bolts with higher yield strengths (either larger diameter or higher strength steel).

EXAMPLE RUN

Inputting the following parameters

$$BF = 2.5 \text{ in/ton},$$

$$G = 120 \text{ lb/ft}^3,$$

$$T = 5 \text{ ft},$$

$$W = 20 \text{ ft},$$

$$RL = 40 \text{ ft},$$

$$BC = 8 \text{ tons},$$

$$NBR = 9,$$

$$NBPR = 4,$$

$$RMR = 50,$$

yields a rock load height H_t = 10 ft, recommended bolt length = 6 ft, bolt capacity = 8 tons, bolt load = 4.8 tons with bolt spacing of 4 ft by 4 ft and an RF = 1.67. Using a bolt with a higher yield strength, 10 tons versus 8 tons, would give a more acceptable RF = 2.08.

OTHER DESIGN SUGGESTIONS FOR CHOOSING BOLT TYPE

After determining support requirements in coal mines, the choice of a roof bolt system—resin or mechanical, tensioned or untensioned—should be based on the following suggestions (*27*).

1. Mechanical bolts are recommended for use in—
   - Harder rock conditions where the rock properties will not adversely affect the gripping force of the anchor;
   - Areas away from blast sites where bolt tension may be lost;
   - Temporary reinforcement systems;
   - Areas close to an advancing face where expected rock deformations will not be significant;
   - Areas where coal bumps and spalling will not be encountered;
   - Applications where bolt tension can be checked regularly;
   - Rock that will not experience high shear forces; and
   - Rock that is not very highly fractured.
2. Grouted bolts, in general, are recommended for use in—
   - The above conditions where mechanical bolts are not recommended;

Permanent reinforcement systems;

Boreholes without continuous water run-off problems or with continuous water run-off that not would interfere with installation; and

Rock without wide fractures and voids, in which significant amounts of grout will be lost.

3. For most coal mines, untensioned grouted bolts are recommended in rock that is highly fractured and deformable as long as adequate bolt installation is feasible. Generally speaking, bolts in more competent strata often require shorter grout columns than do bolts in less competent strata.

4. Tensioned grouted bolts are recommended in areas—

Close to an advancing face where large sudden rock deformations are not expected;

Where coal bumps or spalling are not likely to be encountered; and

Where additional frictional forces in combination with a grouted column may enhance roof stability.

Ideally, resin bolts can be installed in critical areas that may experience considerable deformation and require minimum maintenance, such as in areas that require limited human access. Actually, grouted bolts work well under a wider range of roof conditions found in most coal mines than do mechanical bolts. This assumes proper installation conditions (resin is mixed properly and held in place, and water inflow is not a problem).

A general rule for mechanical bolts is that they cannot be reliably installed in critical areas (or areas requiring permanent support) where significant displacements occur or are likely to occur. This kind of bolting, when working properly and under mild loading conditions, can resist deformation and thus diminish the likelihood of minor displacements for 30 years or longer. Mechanical bolts are not recommended for use in extremely soft rock such as shales and clays that exhibit highly plastic behavior. Unlike resin-grouted bolts, mechanical bolts require constant tension to work properly—a difficult task in highly plastic rock. In such rock it may be wise to use a short-grout-column (point anchor or combination bolt) yieldable bolt that will allow some bolt deformability, particularly near the bolt head (*28*).

MONITORING SUPPORTED ROOF BEHAVIOR

Maintaining roof stability requires routine monitoring, either visually or with instrumentation, of critical areas in the mine, particularly in main entries and along working panels. Most evidence of impending roof failure, such as shown in figure 6, is visual, based on eyewitness accounts. Generally, once this failure becomes widespread, it is difficult to correct. Visual evidence of minor roof failure, such as a loose slab, is normally removed by using a scaling bar. Another technique involves "sounding" the roof by tapping the roof rock to listen and feel for pieces of loose rock, which are mechanically removed. The Bureau has demonstrated the feasibility of using an electronic sounding device that acoustically determines roof rock integrity by emitting a uniform signal input (*29*). (The device is not yet commercially available.)

Installing instrumentation is another way to obtain information on impending failure before it becomes visually apparent. A primary purpose of a roof monitoring program can be to measure the performance of primary support and to determine if and when secondary support will be needed. Measuring roof displacement under supported roof can be an indirect approach for testing support performance. Convergence measurements of roof and floor are easy ways to detect roof, floor, or roof-to-floor displacements. If the floor is known to be relatively stable without heave characteristics, then simple roof-to-floor closure measurements can be a good check on roof deformation. Otherwise, corrections for floor heave should be included. Inserting extensometers into boreholes, using wires, rods, or magnets, is a way to determine absolute or relative displacements at different strata locations in the roof. While not as precise as extensometers, sag bolts, long mechanical bolts without heads or plates, can be installed for easy detection of sag at the roof line. In addition to displacements, differential loading can also be measured at the roof line by instrumenting bolt heads with pressure pads and load transducers. This information can be usefully applied to detect dangerously high load levels and to determine normal load histories of bolts subjected to mining. Load histories of underground roof bolts have been extensively studied by various researchers (*30-31*). Predictably, these studies confirm a typical distinct cyclic loading and unloading pattern taking place when roof bolts are subjected to active mining.

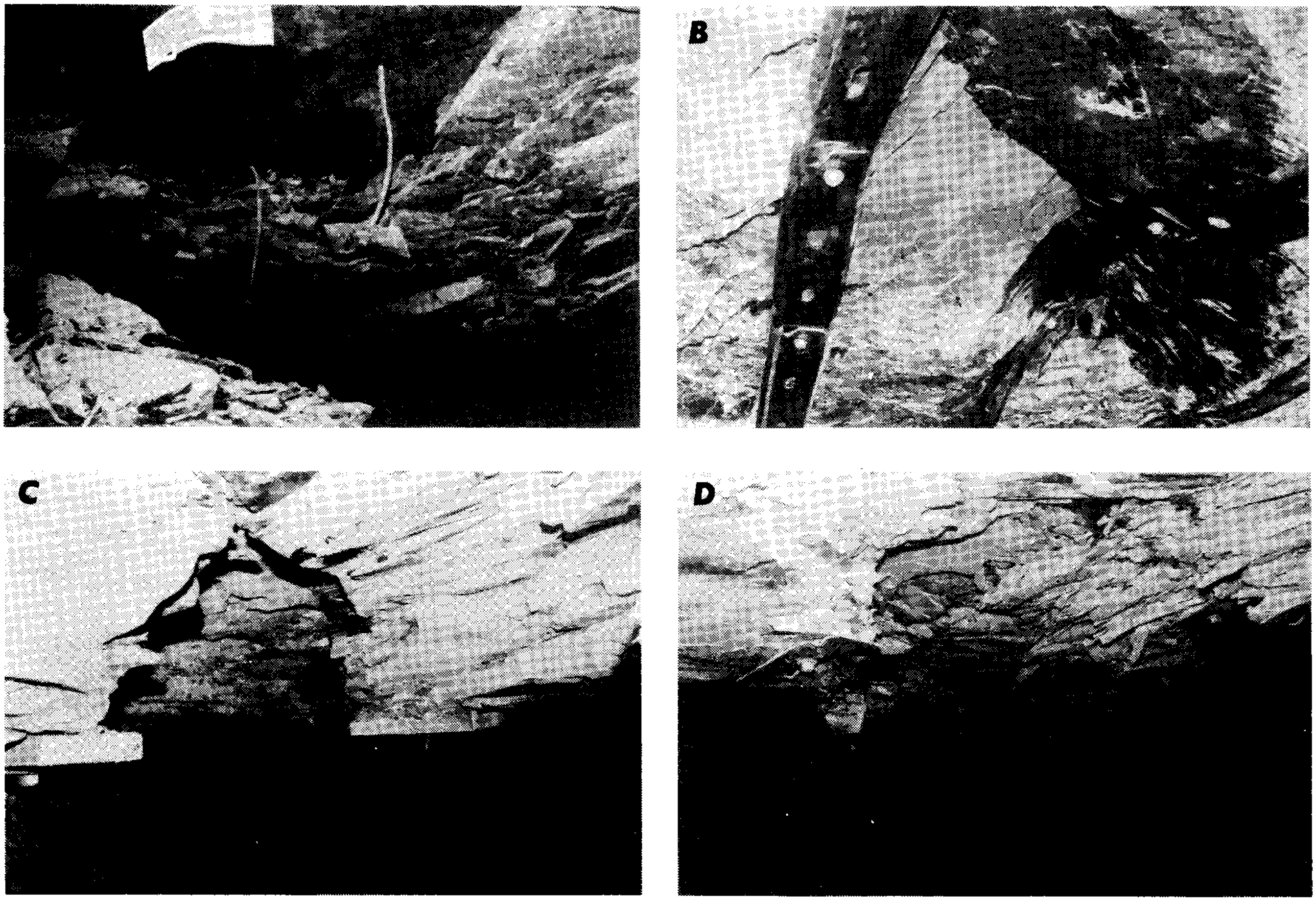

Figure 6.—Visual evidence of roof failure. ***A*****, Fully exposed bolts;** ***B*****, roof spalling near strapping;** ***C*****, roof spalling near bolt;** ***D*****, roof spalling around bolt.**

ROOF TRUSSES

Trusses were introduced in the 1960's as an alternate method of supporting unstable roof when conventional roof bolting by itself was not effective, such as when fallout between bolts becomes excessive or cutter roof is encountered. Trusses, shown in figure 7, are active supports designed to keep the roof in compression, but they can also yield downward as the roof displaces. The net result is that roof stability is greatly enhanced and the integrity of the supports (trusses) remains intact. When used as slings, trusses provide a suspension effect to the roof, transferring loads away from the entry, out over the pillars. Trusses have been demonstrated to be effective for primary or secondary support in conjunction with conventional bolting practices to correct a wide range of roof stability problems. Entry-installed truss systems are sometimes used in problem entry roofs having anomalous geologic features such as faults or sandstone channels. These truss systems are used to correct cutter roofs that sometimes appear along gate roads or near entries that lie in critical zones immediately ahead of the longwall face. In areas where roof falls have previously occurred, trusses are a useful way to stabilize newly exposed roof arches.

Another application for trusses is in three- and four-way intersections, where tensile forces can reach high levels. Compressional forces produced by trusses can be used to diminish high mid-intersection roof tensile forces. Occasionally, longer and larger diameter or higher grade bolts may be used to support, through beam-building, the large volume of rock often associated within the failure dome above the intersection (*17*).

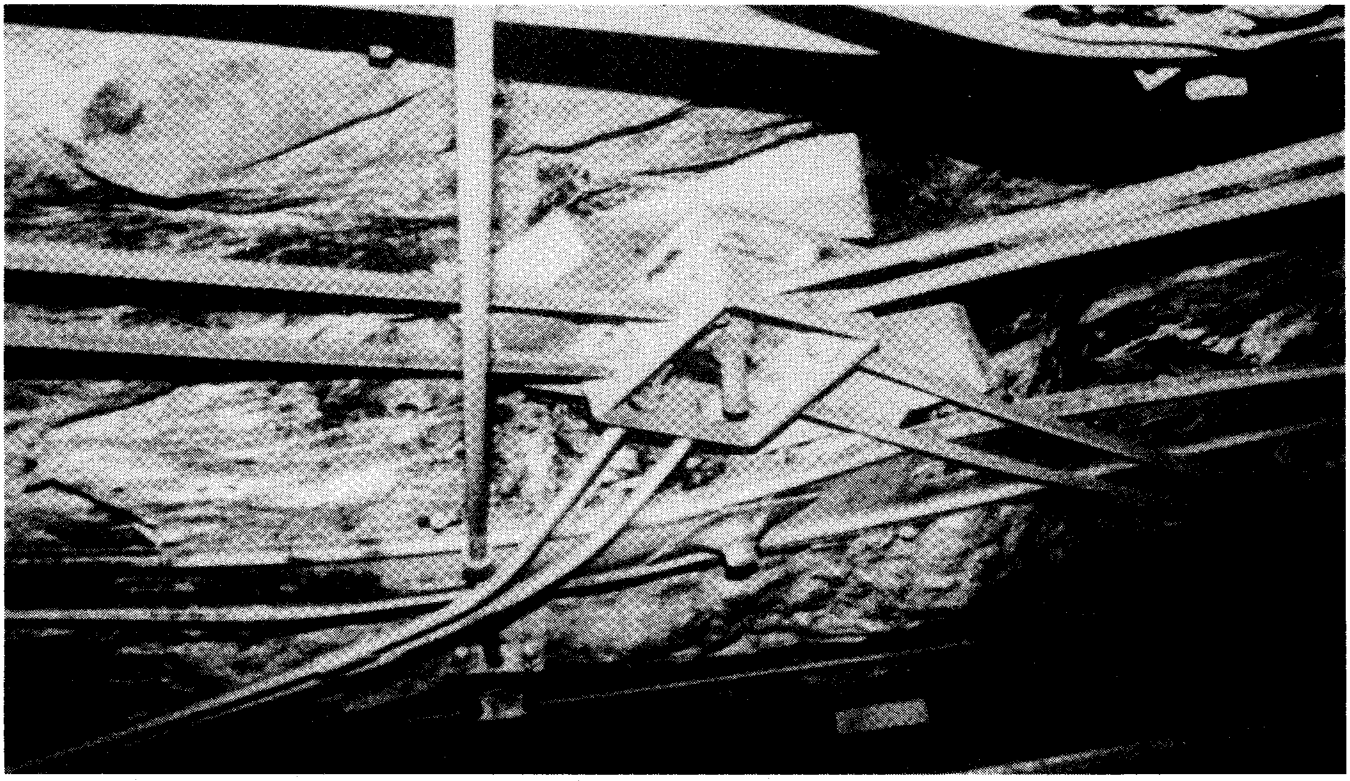

Figure 7.—Trusses can improve roof stability.

SECONDARY ROOF SUPPORT

Supplementary primary support is often needed under heavily loaded and/or weak roof conditions caused by changes in geology. The supplementary support is often installed as needed based on evidence of continuing failure under bolted roof. Examples of supplementary support include cribbing, posts, blocks, planks, additional bolts, angle bolts, and metal straps.

Cribbing and posts remain essential support methods for protecting gate roads from high abutment loads due to the redistribution of stresses created by longwall mining. Regardless of the effectiveness of the bolting system, as shown in figure 8, cribs are often routinely used during periods of high loading.

Abrupt changes in roof geology sometimes require additional bolting and/or other supplementary support. When rolls and slickensides are encountered, support customarily consists of supplementary bolting, angle bolting, metal straps, and limited use of posts and crossbars or rails. Clay dikes or clay veins are also difficult to predict, but usually require roof support consisting of supplementary bolting with cap boards, planks, or metal straps. Roofs encountering sand channels require support similar to that used for clay dikes; however, installation problems are likely when bolting along the margins of sand channels.

Cutters or roof shears are often bolted with long full-length resin-grouted and angle bolts. In severe cases, bolts alone do not work adequately. Often trusses are used across intersections, and posts and crossbars or cribbing must be used along the gate roads experiencing cutter roof. Reorientation of the workings is only done as a last resort and is certainly not encouraged.

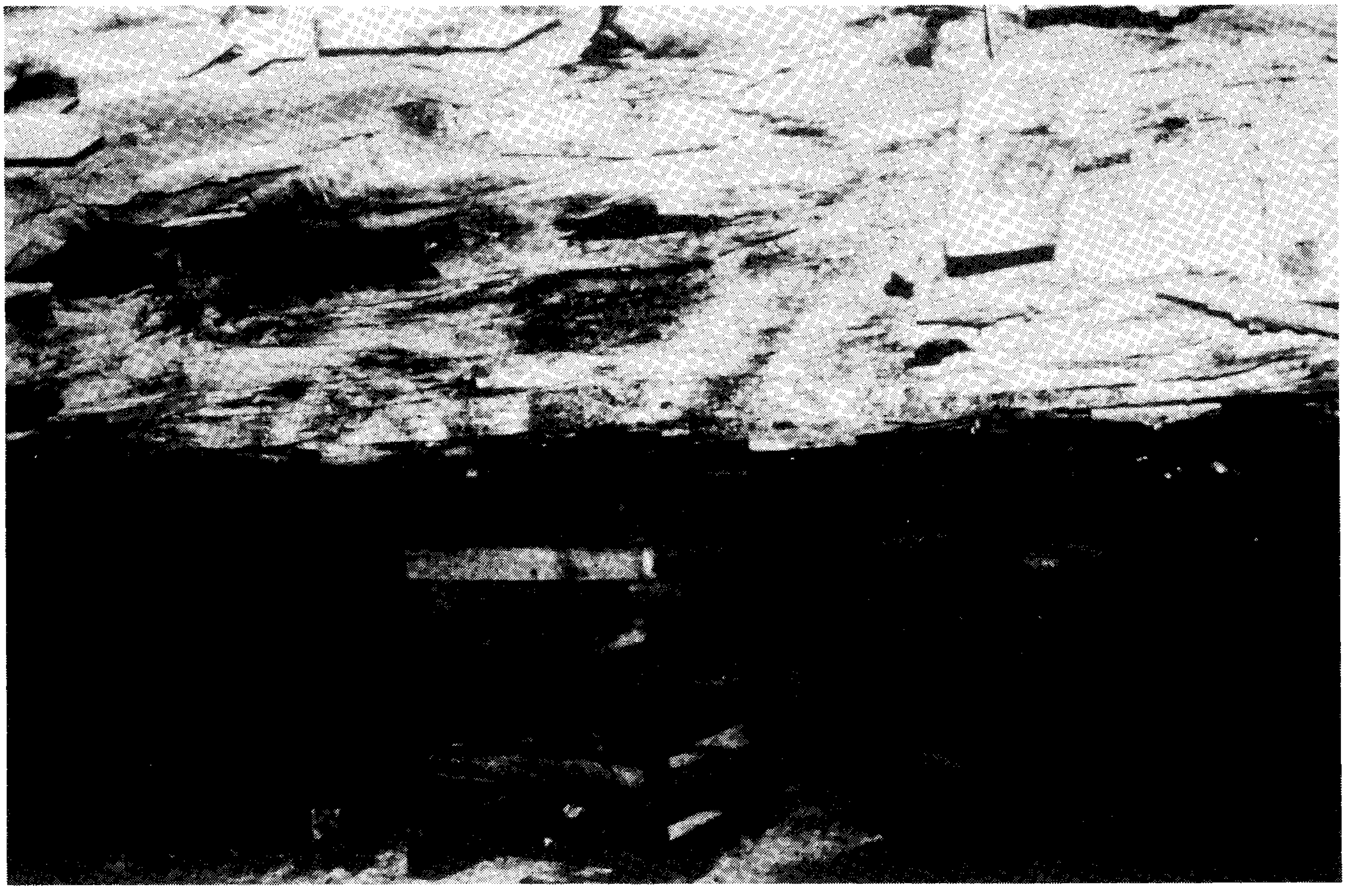

Figure 8.—Cribs effectively shield from high abutment loads.

ADDITIONAL CONSIDERATIONS

Because of changing stress and ground conditions during mining, the roof support requirements may change without warning, resulting in a roof fall. However, according to Given, most roof falls are due to human error because of failure to—

Use adequate temporary support,
Adopt a workable support plan,
Examine and/or identify "bad roof," or
Remove sloughing roof, face, or rib (*15*).

Protection against roof falls begins with proper mine planning, such as adequate pillar and entry dimensions for given local ground conditions. Experience has shown that oversize pillars tend to punch the roof and undersize pillars may yield excessively; both problems result from improper pillar design. The application of an effective bolting system should be used to compensate for roof instability caused by reasons other than improper mine planning and design. The direction of mining will greatly influence rock mass behavior when subjected to a high horizontal stress field. Research has demonstrated that better roof conditions result if the directions of mining coincide with the principal horizontal stress directions (*32*). When proper and timely records are collected, potential roof support problems can be displayed on a hazard map. Such a map is based on an investigation prior to mining to determine stress configurations and geology in and near the coal-bearing strata.

Special roof problems require matching the support to the ground conditions encountered. For instance, if cutter roof is encountered, trusses, angle bolts, and/or longer bolts may be tried and tested for results. Otherwise, other support techniques should be tried until acceptable support is found. Conducting on-site investigations and determining roof support requirements reduces the number of "hits or misses" in a trial-and-error approach to support selection.

One method of continuously assessing roof condition and geology is through the roof bolting operation. Training roof bolt operators to identify and map roof lithology while drilling and to select longer bolts for certain conditions would give the operator greater input in the installation of primary support. This has been shown at one mine to boost operator morale and improve ground conditions significantly (*33*). Other efforts are underway by the Bureau to develop a "smart bolter" that will automatically obtain and report roof strata information (*34*).

Recognizing trends in changing roof conditions that lead to roof problems could be implemented into an empirical-based roof classification system for a specific mine. Useful approaches are to study the geometries, magnitudes, locations, and types of roof falls under certain geologic and stress conditions for the older areas to predict potential problems in newer areas of the mine. One such classification system that incorporates fall geometries showed that a disproportionate incidence (60% to 80%) of falls were related to areas experiencing significant amounts of rib rashing (*35*).

CONCLUSIONS

Roof bolting remains an important element of ground control in underground coal mines. This report has shown that the correct application of roof bolts involves a thorough understanding of the roof rock, stress conditions, bolt behavior, and interaction effects between the anchor and roof rock. History has shown that roof bolting, when properly planned and applied, significantly decreases the size and occurrence of roof falls. Identifying key parameters that influence roof behavior should be the primary goal of a data-monitoring system so that the proper primary and secondary support strategy can be applied and tested.

Choosing the proper support strategy requires first determining the support requirements through calculations, nomograph, or empirical means. Matching the support to the support requirements requires knowing what works best under different conditions and knowing the limitations of the support type chosen. Historical evidence suggests that the problem of roof support can be variable from mine to mine and should not be handled in a generic manner. Instead, the best approach to follow is to identify the important variables (depth, stress field, geology, rock quality, etc.) and then determine appropriate support methodology for each site-specific case.

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