Development of Stress Measurements and Instrument Placement Techniques for Longwall Coal

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ABSTRACT: Western coal mines are operating under increasingly challenging ground conditions. Researchers at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health are cooperating with mines to evaluate how these conditions affect mine opening stability and related miner safety. A system was developed to monitor rock and coal stresses during mining of an entire longwall panel. The system was designed to generate data in near real time to evaluate rock behavior in roof strata and the onset of hazardous conditions as overburden stress was redistributed over working entries during gob formation. Computer simulations and in-mine evaluations were used to optimize instrument placement. A prototype packer assembly was designed and tested for installing sensitive instruments in a mine roof. This paper provides background information on the stress monitoring concept and focuses on the development of instrument placement techniques and the prototype packer assembly.

1 BACKGROUND

1.1 *Stress monitoring system concept*

Researchers at the Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health (NIOSH), in cooperation with a mining company, have developed and continue to refine a stress monitoring and reporting system. The initial objective was to determine if stress monitor-ng instruments could gather sufficient data to recog-ize the conditions leading to coal bumps so these conditions could be mitigated with engineering con-trols before a catastrophic event. During use of the monitoring system, it became apparent that the system could also be a valuable research tool in eval-uating rock behavior surrounding mine openngs. The system could also be used to study the technologies designed to maintain safe openings in more chal-lenging ground conditions. Below is a description of the system developed to meet these objectives.

The stress monitoring system is comprised of a cluster of instruments (figure 3) placed strategically to detect changes in stress and displacement at a pre-selected site in the headgate of an operating long-wall. These stress changes are initiated near the longwall face as load is redistributed following coal removal and gob formation. Stresses are transferred through roof strata from the area of active mining back to the instrument site. A data acquisition sys-tem retrieves data from these instruments at pre-selected time intervals. Raw data are then processed and reduced and used to generate graphs. These graphs illustrate trends that may be used to evaluate (1) behavior of roof strata above mine openings, (2) imminent catastrophic events, (3) effects such as typical yield pillar movement that are not a safety concern but may distort needed information, and (4) placement and type of additional support or other safety intervention.

1.2 *Phase 1 research*

In the first phase, a monitoring system was develop-ed and used to monitor stresses during the mining of an entire longwall panel (Zahl et al. 2000). Instru-ments were clustered in two panels, a yield pillar, and the immediate roof and floor of a two-entry longwall gateroad. Data were gathered continuously for 6 months from a variety of stress and displace-ment measuring instruments as longwall mining pro-ceeded from the start-up room 700 m (2300 ft) away and moved toward and past the instrument cluster.

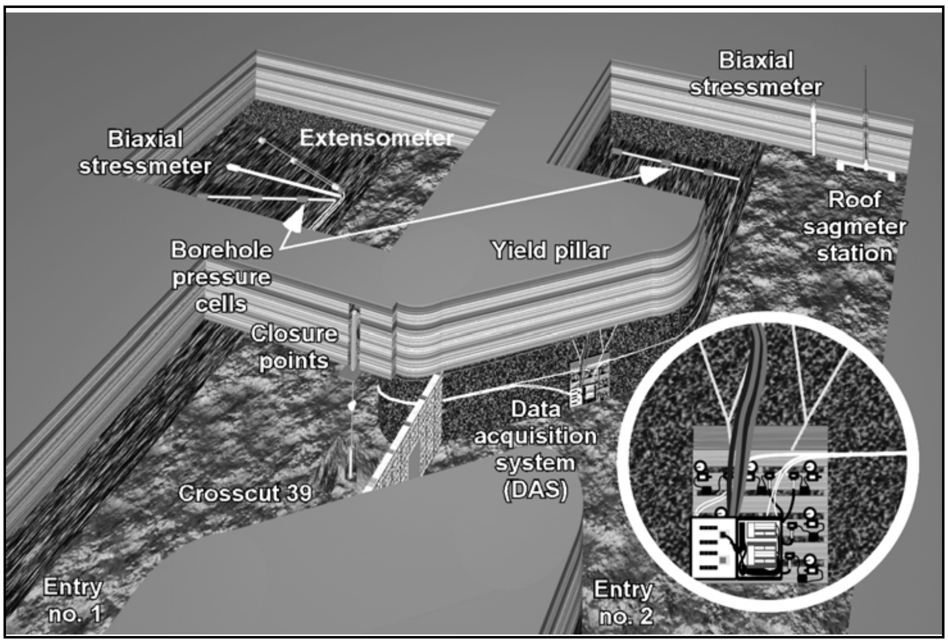

Figure 1.—Computer-generated cutaway showing examples of instrument placement.

Researchers and the mine's technical staff evaluated these data with respect to bounces, bumps, and bump mechanisms. Selected graphs were also presented to mine foremen on a periodic basis to test the graphs' usefulness in identifying imminent bump conditions. One of these graphs was used to compare vertical biaxial stressmeter measurements from the stress monitoring system with bounce or bump events reported by miners (table 1) and seismic events from a microseismic system (figure 2). This graph also illustrates the level of detail that data trends provided, although it was apparent that more research was necessary to interpret the meaning of these types of data trends fully. Evaluation of many data trends indicated there was a potential for using this type of system as an assessment or hazard recognition tool and hence to enter a second phase of research. A sequence was developed for installing and using a stress monitoring system, as well as providing a basis for development of specific components (table 2).

1.3 *Phase 2 research objectives*

Hundreds of stress graphs were generated in the first phase. Those using horizontal stress changes measured by vertically installed biaxial stressmeters appeared to be the most sensitive to events farthest away. For example, horizontal stress changes measured by these stressmeters became evident when the working face was 518 m (1700 ft) away from the instrument site. This was significantly farther than the hundred meters or so typical of borehole pressure cells in coal. It is known that horizontal stresses are an integral factor of roof failures. For these reasons and others (Maleki 1995), SRL researchers believed that use of horizontal stress data showed the most promise for assessing rock behavior and recognizing hazards. Evaluation of research needs at the close of first phase indicated that top priority items were (1) selecting optimal locations to place the monitoring instruments and (2) a more reliable system for installing biaxial stressmeters vertically into the mine roof. The remainder of this paper describes these approaches, explains the equipment and processes, and discusses the application of these developments.

2 PREINSTALLATION TESTING

2.1 *Approach for testing*

To determine where instruments should be located more effectively, researchers evaluated a number of techniques that could be employed both in and out of the field before the instruments were placed. Preinstallation tests resulted in a new approach and new tools to the site selection step in the installation process outlined in section 1.2. The most helpful preinstallation tests were (1) two-dimensional FLAC modeling analyses, (2) evaluation of roof borehole logs for material properties and the extent of roof strata, and (3) measurement of rock stiffness at selected roof horizons based on borehole logs and FLAC modeling.

Table 1.—Observed bump-related events near instrument site

Event No.	Date	Face location	Event	Comments
1	2/5/00	60-80 shield	Coal blowout	Crews avoid this area because of conditions.
2	2/7/00	45-50 shield	Shield yielding	
3	2/85/00	28-38 shield	Coal blowout with bump	Strong bounce reported; downtime to put pan line back together.
4	2/9/00	32-45 shield	Coal blowout with bump	Larger chunks blown into shields; power knocked off to shearer, which was in area headed toward headgate.
5	2/9/00	10 shield	Coal blowout with bump	Not as severe as earlier bump, but did blow coal into shields. Floor heaved and power killed to shearer. This shearer also in area headed toward tailgate.
6	2/9/00	40 shield	Coal blowout with bump	Fine coal chunks blown into shields; killed power to shearer. Shields also yielding in this area.
7	2/9/00	40 shield	Coal blowout with injury	[6:35] Face blew out, sending large chunks of coal into shields. Employee was struck, resulting in fractured leg.
8	2/17/00	Tailgate	Coal blowout with bump	[10:00] Bounce in tailgate; shearer was in area. Coal blowout knocked lights off of two shields. Equipment damage was reported.
9	2/18/00		NA	Minor bouncing, no major events reported.
10	2/24/00	No. 2 entry headgate	Bounce	[21:00] Big bounce felt, no damage reported. NIOSH system reported bounce, as did Univ. of Utah system.
11	2/24/00	Headgate and tailgate	Bump	Bumps in headgate and tailgate areas when shearer pulled into area.
12	3/5/00	Stage loader	Roof fall	[0:30] Roof fall over stage loader. Longwall shut down to reestablish walkway along stage loader.
13	3/7/00			[19:15] Earthquake triggered several roof falls and rib sloughs. Magnitude 4.1 on national and state seismographs.
14	3/17/00	Headgate	Roof fall	[13:45] Roof fall over stage loader shut down longwall.
15	3/29/00	Headgate	Roof fall	[12:20] Roof fall over stage loader. Production stopped until later in afternoon.

Table 2.—Stress monitoring system process

Step	Task	Objectives
1 . . .	Site selection	Determine most hazardous locations, identify zones away from surface sloughage.
2 . . .	Instrument selection	Select instruments proven capable of measuring expected stresses, determine amount of redundancy required, and ensure constraints posed by the mine and drilling are met.
3 . . .	Instrument installation	Meet instrument installation requirements, schedule activities to minimize interference with ongoing mining operations.
4 . . .	Install data acquisition system	Determine monitoring intervals, develop a data retrieval plan
5 . . .	Data management	Create reduction matrices for raw data, create time- and location-dependent graphs for stress changes.
6 . . .	Data evaluation	Correlate data trends to observed events and other relevant data collection systems, discuss and interpret results with people having differing expertise.

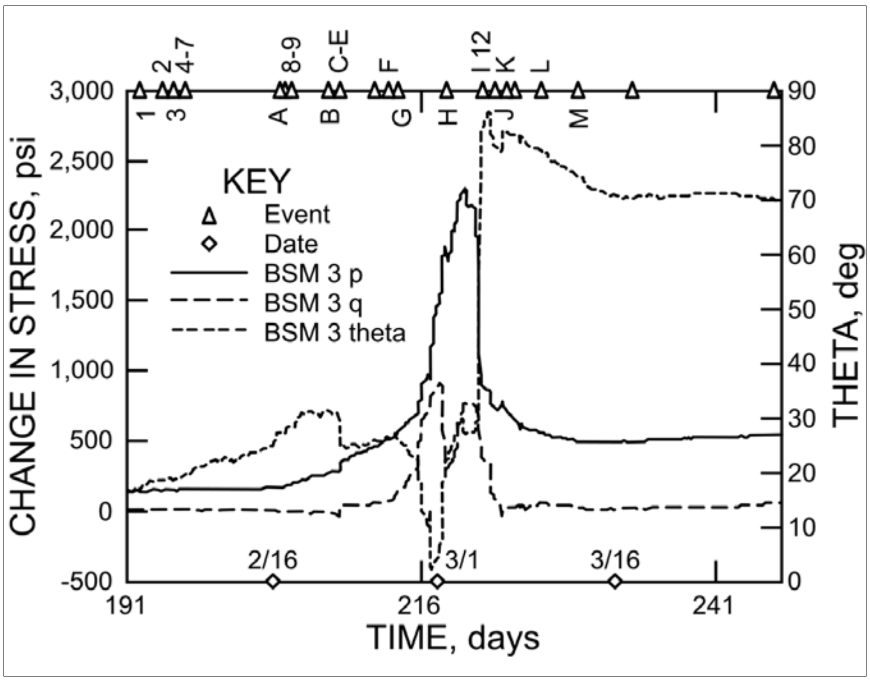

Figure 2.—Change in stress versus time for a vertical biaxial stressmeter. Data trends leading to actual events are shown.

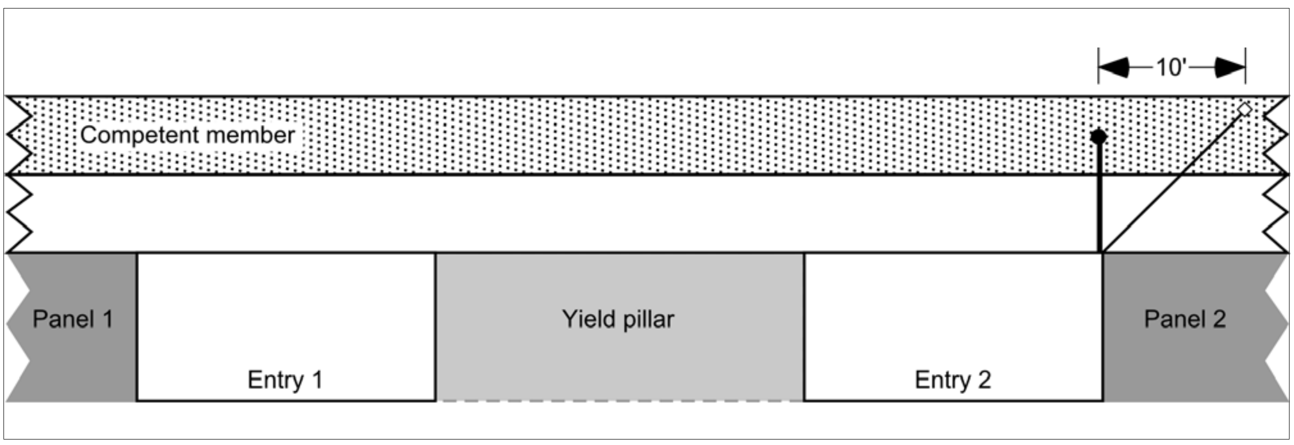

Figure 3.—Cross section of mine at the instrument site.

2.2 *Finite-difference modeling*

A two-dimensional, finite-difference model (FLAC) was used to simulate stresses in a two-dimensional cross section of a coal panel, entry 1, yield pillar, and entry 2 (Itasca 1998) (figure 3). The model was used to identify areas in the mine roof above entry 2 that would undergo the largest horizontal stress changes as a result of mining. These results, along with practical considerations such as borehole depth and observable host rock degradation around the entry, were used to target a location for the biaxial stressmeter.

The two gateroads, longwall panel, and surrounding mine structure were modeled in plane strain with a 102- by 102-m (336- by 336-ft) vertical cross section oriented perpendicular to the gateroads. Strata dipped 6° in this plane. Based on drill hole logs provided by the mine staff, each stratigraphic layer greater than 0.3 m (1 ft) thick was represented in the 28,224-element finite-difference mesh. Elastic properties and tensile strengths used in the model were obtained from material test results that were also provided by the mine staff. Because the values for cohesion and angle of internal friction were unreasonably large when they were derived from strength values, average textbook values were used (table 3). Secondary horizontal principal stresses obtained from overcore measurements were rotated into the model's plane for the initial horizontal stress field, and vertical stress in the model was assumed to be -19.3 MPa (-2800 psi), based on the force of gravity on the overburden material (table 4). The vertical boundaries of the finite-difference mesh were fixed in the horizontal direction and the horizontal boundaries were fixed in the vertical direction.

Table 3.—Material properties used in finite-difference model

	Young's modulus		Poisson's ratio	Cohesion		Angle of internal friction,	Tensile strength	
	GPa	10^6 psi		MPa	psi	deg	MPa	psi
Roof sandstone . .	23.4	3.40	0.26	27.20	3945	30	7.52	1091
Roof siltstone	19.3	2.80	0.23	22.81	3309	30	8.91	1293
Roof mudstone . . .	45.2	6.55	0.42	20.72	3005	26	5.03	730
Coal	2.96	0.43	0.38	7.73	1122	30	1.93	280
Floor mudstone . . .	23.0	3.34	0.25	26.73	3877	30	26.73	3877
Floor sandstone . .	51.9	7.53	0.21	21.49	3117	30	24.56	3562

Table 4—Initial stresses used in finite-difference model

Direction	Magnitude	
	MPa	psi
S_{xx}	-22.04[1]	-3196[1]
S_{yy}	-19.31	-2800
S_{zz}	-13.16	-1908
S_{xy}	5.31	770

[1] Compression is negative

To identify the areas of highest horizontal stress change in the mine roof above entry 2 induced by longwall mining, the excavation of a large room approximately 12 m (40 ft) wide and 3 m (10 ft) high was simulated southwest of entry 1. The entire longwall was not modeled to reduce boundary effects on stress changes around entry 2. Results from the numeric model indicated that the location of the highest horizontal stress increase was above the yield pillar between entries 1 and 2. In general, the magnitude of these stress changes decreased as distance from the excavated longwall increased. The different deformation moduli of the roof strata was reflected in the magnitude of stress change. Hori-zontal stress changes in mudstone in layers from 1.2 to 3.7 m (4 to 12 ft) above entry 2 was 1.6 to 2.7 times larger than in adjacent sandstone layers. The mudstone modulus used in this analysis was 1.9 times larger than the sandstone modulus.

These numerical modeling results were used as a guide for placement of a biaxial stressmeter in the mine roof above entry 2. The highest calculated horizontal stress change was above the yield pillar. However, this location was not considered because the stress changes at this location reflect yielding typical of a yield pillar and would mask stress changes generated by the more critical loading between the instrument site and active mining. Approximately half of this pillar yielded in the model. Similarly, failure zones were identified above entry 2 that would mask critical loading. Observations of the roof rock in entries has shown separation of material close to the roof and rib. Also, results from the FLAC analysis indicated that instru-ments should be placed outside a 3.3-m (10-ft) zone adjacent to entry 2. Because of the higher magnitude of stress change in the relatively stiff mudstone layers and possible raveling caused by the yield zones, the stressmeter was targeted for installation in competent roof mudstone in a 8.5-m- (28-ft-) long borehole angled 45° upward in entry 2 (figure 3).

2.3 *Geologic interpretation and borehole logging*

Stress measurements are affected by the physical properties of each members through which the stress is transferred. For example, stress flows most readily through a horizontal member with the highest stiff-ness and the greatest continuity between the working face and the point of measurement. Geologic pro-files were plotted on fence diagrams created from a roof core logging program in gateroad entries. These fence diagrams allowed researchers to evaluate the continuity of the strata and use this information to aid in selecting a roof member. Unfortunately, the depositional character of the roof rock was so com-plex and discontinuous that a single member could not be identified that encompassed the entire stress transfer zone.

2.4 *In-mine determination of strata stiffness*

During prior installation of vertical biaxial stress-meters, SRL researchers were primarily concerned with developing placement techniques. At that time, instruments were placed in a competent zone at a horizon above roof degradation and at an angle perpendicular to bedding. Experience with roof rock behavior and analyses of FLAC modeling results confirmed that stress changes are much higher in layers of roof strata with a higher modulus of elasticity. Placing a biaxial stressmeter in the stiffest roof member resulted in obtaining measurements that were the most sensitive to changes farthest away from the instrument site. Maximizing the distance over which the stress monitoring system can detect changes is a research objective that will increase the utility of this tool.

Although mine records provided physical and mechanical properties for typical lithological cross sections, large changes in the lithology of boreholes were observed near the instrument site. The complexity of the deposition and changes of material properties within the mudstones and siltstones made visual identification of the stiffest zones impossible. For this reason, it became necessary to determine the stiffest member of the immediate roof lithology so optimum horizons for placing a biaxial stressmeter could be identified. The search for a method led researchers to a development by Goodman (1980), Meyer (1974), and Heuze (1984), who built a NX plate-bearing device for measuring the modulus of elasticity in a borehole. This device is known as the Goodman jack. There is still debate on the ability of this method to provide measurements of Young's modulus comparable to laboratory tests. However, SRL researchers agreed that this method could provide a reliable comparison of stiffness among alternative zones tested in a borehole.

Field tests using the Goodman jack were completed on boreholes located 9 m (30 ft) from the preselected installation site for the biaxial stressmeter. The NX borehole was drilled, and a series of four tests were run, beginning at the deepest point (6 m [20 ft] into the roof) and continuing toward the collar of the hole. Test horizons were determined based on drilling characteristics and assessment of the logged core retrieved from the borehole. Results from the test showed a range of 4 moduli from 12.4 GPa (1.8 million psi) at 3.4 m (11 ft) from the collar of the borehole to 19.3 GPa (2.8 million psi) at the 6-m (20-ft) horizon.

The Goodman jack is useful if reliable measures of the modulus of elasticity are not available for target horizons. This method used in conjunction with a geologic evaluation of borelog data to determine the extent of the stiffest members provides an effective way to determine where to position biaxial stressmeters for the stress monitoring system.

3 INSTRUMENT PLACEMENT

3.1 *Development of instrument placement method in a mine roof*

The research team had previously selected biaxial stressmeters that used vibrating wire technology to monitor long-term stress changes because of the low electronic drift inherent with this instrument and the overall superior performance of biaxial stressmeters in previous tests (Larson et al. 2000; Seymour et al. 1999). Discussions with instrument manufacturers indicated that no method was available to install vibrating wire stressmeters in an upward-oriented borehole, so researchers developed and tested a number of methods using prototype packer assemblies to meet the installation requirements for this instrument.

A number of difficulties were encountered in laboratory and field tests while trying to grout a biaxial stressmeter vertically into a borehole. Primary design objectives were to (1) install the instrument in a borehole longer than seam height, (2) maintain the integrity of the grout around the instrument until the grout sets, and (3) control instrument orientation during placement.

Although researchers had experimented with various designs in the first phase of research, none proved reliable. Particular design problems were that (1) assemblies were difficult to install deeper than seam height because of the complexity of the plumbing needed for grout injection and the tight tolerances of the assembly in the borehole, (2) venting tubes malfunctioned, which did not allow installers to determine if adequate grout had been delivered to the borehole, (3) the seal between the packer core and the outer bladder failed, (4) maintaining instrument orientation was difficult because of slipping threads in the multiple joints in the setting rods.

A second-generation prototype was designed and tested in both the laboratory and the field (figure 4). The instrument appeared to have successfully overcome the previous design inadequacies (figure 5). Success of the new system was based on changing the basic design approach so that all rigid components of the assembly are kept to a length of 2 m (7 ft). This allows installers to insert the assembly easily within the seam height of typical coal mine entries. On installation, there are four trailing flexible lines—the instrument cable, the

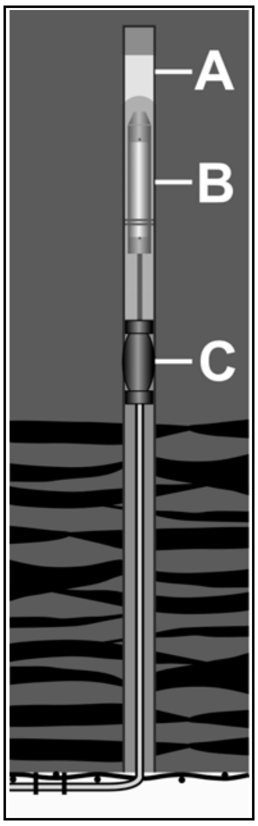

Figure 4.—Cross section of final placement in a borehole (A) of a biaxial stressmeter (B) and packer (C).

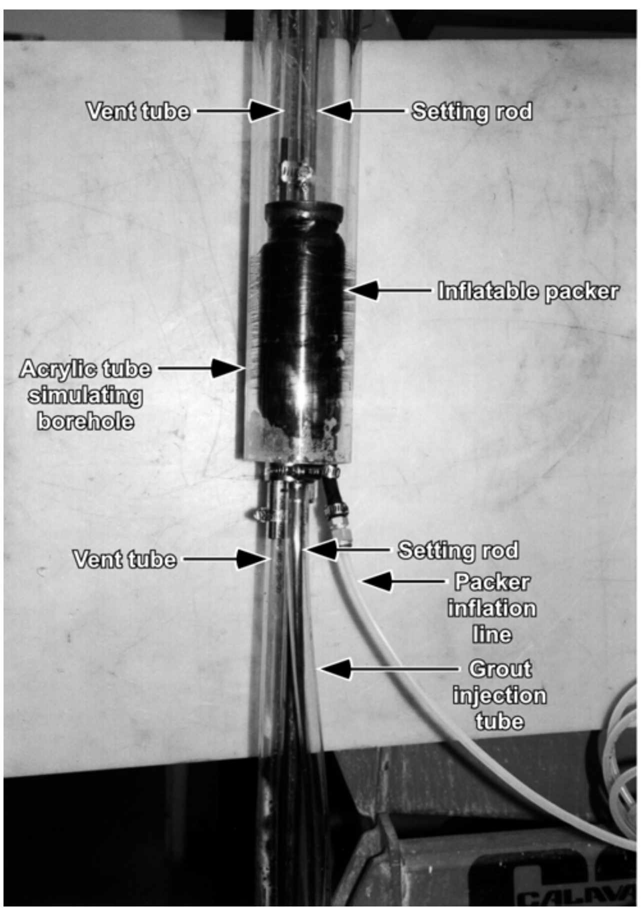

Figure 5.—New prototype packer showing trailing lines.

packer inflation line, the grout injection tube, and the vent tube. The assembly is installed with standard setting rods and a specially fabricated setting head designed to allow proper instrument orientation. The packer seal problem was solved by using a simple bicycle inner tube that requires no special sealing surfaces to maintain pressure. Venting problems were solved by increasing the size of the vent tube so grout could be pumped from the borehole through the vent line and made visible to the installers so they can ensure proper grout placement.

3.2 *Process for stress monitoring system installation and use*

Current plans call for further development and testing of this stress monitoring system. However, the authors would like to suggest the following installation process. Our aim is to evaluate the feasibility of using a stress monitoring system as a hazard recognition tool in selecting safety intervention strategies.

1. If mine engineers and managers determine there may be ground control concerns for a longwall panel on development, they should identify entries and approximate locations (within a 610-m [2000-ft] interval) of where ground control problems are most likely to occur based on past experience.
2. A stress monitoring system site would be selected 61 to 152 m (200 to 500 ft) outby the area of concern, with the data acquisition system located farthest outby so as to maintain it as long as possible as mining encroaches on the system.
3. Some or all of the preinstrumentation tests and evaluations (geologic bore logs, FLAC modeling, and Goodman jack) would be completed to determine optimum instrument placement.
4. A stress monitoring system should be installed and a monitoring program implemented that allows for periodic downloading of raw data, generation of characteristic curves, and interpretation of results by mine engineers.
5. Engineers and mine managers should interpret the data trends continually and evaluate these data trends after additional support or other safety intervention steps are taken.
6. Researchers should catalog and evaluate characteristic curves to understand the applicability of the system and make further developments to increase reliability.

4 DISCUSSION AND CONCLUSIONS

4.1 *Application of the stress monitoring system*

Researchers have developed two uses for the stress monitoring system. The first is as a research tool to assess mining-induced rock behavior and load redistribution dynamics near active mining and understand and evaluate the effectiveness of the many technologies the mining industry is using to maintain structurally safe underground working areas. The need for these types of assessments will dramatically increase as the coal mining industry deals with increasingly challenging conditions as coal mines are developed deeper and in less stable ground.

The second use is as a production tool to recognize hazards during mining operations. Actual changes in horizontal stress measurements should be compared with characteristic data trends to identify the nature and location of potential ground control hazards in the working entries between the working face and the instrument site. From this, mine managers may respond by adding necessary support or utilize some other appropriate intervention tactic to prevent ground control failure and subsequent injuries or fatalities.

Extremely competitive market conditions, coupled with lower injury and fatality rates in recent years, appear to make the stress monitoring system too costly and complex to be implemented during mine production in the near term. In the future, this system could become practical during production if (1) its cost and complexity were reduced, (2) mining conditions became more hazardous, or (3) coal company profitability increases (factors that are all probable in the long term). If a proof of concept is successful, developing this tool now may be of value so that it is available when the mix of these three conditions is sufficiently met.

4.2 *Discussion of results*

The value of using this type of stress monitoring system as an assessment tool has been demonstrated throughout its development in the research program. Researchers and mining engineers have used results for assessing mining-induced rock behavior and load redistribution dynamics near the active mining face. This tool needs to be developed further by collecting characteristic data trends in varying scenarios so these trends may be correlated with specific failure mechanisms and load redistribution dynamics. Armed with this information, researchers could better assess the engineering controls needed under more hazardous conditions as mining proceeds deeper and into less stable ground.

The concept of using this tool for recognizing hazards during production is predicated on a number of assumptions. This research program has taken these assumptions in a selected order to test them and from the results establish a proof of concept.

The first assumption researchers made was that horizontal stresses can be accurately measured in a mine roof during a mining operation. To date, research has focused on developing a stress monitoring system by field testing various configurations in operating longwall headgates. The objective was to measure changes in horizontal stresses accurately and develop strategies for determining optimum instrument placement techniques and locations. Results show that NIOSH has successfully developed devices and methodologies in combination with existing instruments and data acquisition technologies to make useful horizontal stress measurements in roof strata.

Another assumption was that irrelevant factors influencing horizontal stress measurements can be “filtered out” so as not to distort data trends in a way that interferes with detecting imminent catas-trophic events. Examples of such irrelevant factors are (1) stress redistribution due to normal yield pillar dynamics, (2) large changes in ventilation air temperatures or pressures, and (3) typical delamination or sagging of the immediate roof strata over entries. In research to date, additional stress and displacement measuring devices have been installed in the roof and coal pillars and panels to monitor changes in the immediate area of the instrument site. This allows researchers to compare data trends from these instruments to account for possible influences of an irrelevant nature. However, more baseline data are required to determine characteristic data trends and their interpretation.

Another assumption is that catastrophic events are initiated by poor gob caving or some other mechanisms that (1) develop slowly enough to be detected and resolved before the event, (2) are not masked by potentially changing geologic properties through which stresses are transferred, and (3) produce horizontal stress changes at the instrument site. Another way to pose this assumption is that a stress monitoring system can be designed to discriminate between “expected” characteristic data trends that indicate “target entries are safe to work in” as the face advances and “abnormal” characteristic data trends that indicate that failure is imminent and that existing support or other engineering controls are not adequate. In addition, the stress monitoring system must provide data that allow engineers to determine the location of the potential event soon enough for the planned engineering control to be effective.

Researchers began addressing some of the issues in these underlying assumptions. The concept of preinstallation testing was initiated to better understand the effects of geology and mine openings around an instrument site. Finite-difference modeling was devised to select instrument placement sites to intercept maximum stress changes relevant to imminent catastrophic events. Goodman jack evaluations were devised to identify the stiffest strata in the immediate roof, which will, by definition, transfer the greatest amount of horizontal stress. Borehole log evaluations were devised to identify the extent of the stiffer zones through which horizontal stresses are transferred. Future development of characteristic data trends should focus on accounting for the material properties of the strata through which these horizontal stresses are transferred as well as the loading dynamics of the gateroad pillars and adjacent panels and the load transfer dynamics surrounding the active mining face.

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