AUTOMATED MONITORING AND GEOTECHNICAL EVALUATION FOR GROUND CONTROL IN LONGWALL MINING

By John P. McDonnell,[1] Robert M. Cox,[1] and John P. Dunford[2]

ABSTRACT

The U.S. Bureau of Mines (USBM), utilizing commercially available monitoring system technology, is developing computer-assisted processing and analysis techniques for near real-time evaluation of underground coal mine ground conditions. The combination of existing mine monitoring system and sensor technology with automated computer analysis techniques enhances the acquisition, analysis, and display of geostructural data from high-production longwall mining operations.

Underground monitoring system instrumentation networks have been installed at three longwall operations (one in western Colorado and two in central Utah) to collect ground control information to aid in evaluating ground conditions along high-production longwall faces and surrounding gate road entries. The data typically consist of pillar, panel, and shield pressure changes, and strata movements.

Samples of monitoring system results presented in this paper, which combine mine structure data with other information, such as geologic conditions, have provided near real-time information on stress transfer, mine structure pressure buildup, and strata movement associated with several ground control events. The monitoring system network provides the mine operator with information to rapidly identify and manage potentially hazardous ground conditions while mining is in progress.

INTRODUCTION

Ground control is a critical factor in maintaining the safety and efficiency of modern, highly mechanized, and productive underground coal mines. Advancements in the mechanization of underground production equipment have resulted in increased longwall production and panel retreat rates. Rapidly changing ground and stress conditions that accompany high mining rates challenge mine operators to maintain safe working conditions.

The design, implementation, and management of ground control systems are difficult due to (1) the large number of parameters affecting the stability of coal mine openings, (2) the variation of parameters throughout the mine, and (3) the lengthy time required to thoroughly analyze ground conditions and support requirements (1).[3] Mine management seldom has sufficient time or resources to review all possible control techniques, and controls are often implemented too late to prevent major problems. The USBM is conducting research to improve the management of ground control systems by combining minewide monitoring technology with automated analysis techniques.

Advances in sensor technology and monitoring systems have improved remote acquisition of underground mining information. Minewide monitoring systems, used to manage many diverse mining activities such as conveyor and ventilation systems, are becoming commonplace in U.S. mines and are improving safety and productivity (2).

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[1]Mining engineer, Denver Research Center, U.S. Bureau of Mines, Denver, CO.

[2]Mining engineer, Spokane Research Center, U.S. Bureau of Mines, Spokane, WA.

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

Real-time data acquisition, coupled with automated processing, provides important decisionmaking tools for mine management (3-4).

The USBM research effort to automate the acquisition and analysis of ground control information is to utilize existing monitoring and sensor technology for data collection, storage, and processing. Data acquisition and analysis are being accomplished using commercially available monitoring system components, instrumentation, and software packages and custom software routines.

This paper provides a general overview of the in-mine application of the monitoring system technology and presents several examples of monitoring system data collection and processing results related to ground control events.

MONITORING SYSTEM COMPONENTS

The instrumentation networks were designed to provide real-time ground control information and data from operating longwall mines for subsequent automated analysis and evaluation tasks. The monitoring system also served as a test facility to evaluate the effectiveness of various instruments and sensors for measuring ground control parameters. The entire system is comprised of commercially available equipment, and all underground components located in return airways are approved by the U.S. Mine Safety and Health Administration (MSHA).

Discussion of the monitoring system components will focus mainly on the instrumentation network installed in the Colorado mine because of the magnitude of the system demonstration there. The data from the Colorado mine, where the USBM has its own monitoring network separate from the mine, are monitored remotely from the mine surface and the Denver Research Center (DRC) mine monitoring laboratory. Computers linked to the DRC system process the mine structure data and generate graphics displays to permit near real-time detailed evaluation of strata control information. The instrumentation networks at the two Utah mines are connected to the respective mine's monitoring system, where the data are collected and stored on the mine's own monitoring and computing equipment (5).

The primary ground control parameters measured are shield-leg pressures, ground pressures in the gate road structure (pillars and panels), and strata movements (roof-bed separation and gate road entry closure). Figure 1 shows a generalized schematic of the monitoring system network. The instrumentation layout was designed to continuously monitor shield loading on the longwall face, and ground pressure and strata movement changes at several longwall gate road sites having different pillar configurations and geologic conditions. The numbers of sensors, locations of various monitoring system components, and cable routes and lengths were adjusted throughout the monitoring program as necessary, depending on the specific instrumentation layout (1).

COMPUTER CONTROLS

The main computer control station, shown in figure 2, is located at DRC and consists of a Conspec Model 400 Mine Monitoring System computer linked to various graphics and data processing computers. The DRC computer controls communication with the sensors at the mine via a dedicated phone line and displays sensor status. Coupled with the primary computer is a graphics system installed both on a separate computer at DRC and a computer at the mine surface. The graphics computers provide real-time color displays of sensor data and alarm conditions, permanent storage of data on magnetic disk, and printing of detailed reports.

The mine surface installation consists of two modems, a communication monitoring switch, and a secondary computer system for data display and storage. The modems control communication between DRC, the mine surface, and the underground control station (UCS).

UNDERGROUND COMPONENTS

The UCS consists of trunk barriers for the various gate road sites, trunk extenders that supply power to the individual trunk cables, a modem for communication to the mine surface, and an intelligent area controller (IAC). The IAC allows personnel to access sensor information while underground during installation and troubleshooting operations. The UCS is generally located at the outby end of the panel being mined, near or in the main entries, and near an available power supply.

Sensors are connected to the monitoring network through an electronic interface (accessor), which converts the analog signals to digital form for communication and data transmission over trunk cables to the UCS. Each accessor is mounted adjacent to the sensor, as shown in figure 3, to reduce sensor cable signal loss and to minimize damage to sensor cabling. The accessors communicate with the UCS over four-conductor shielded trunk cables
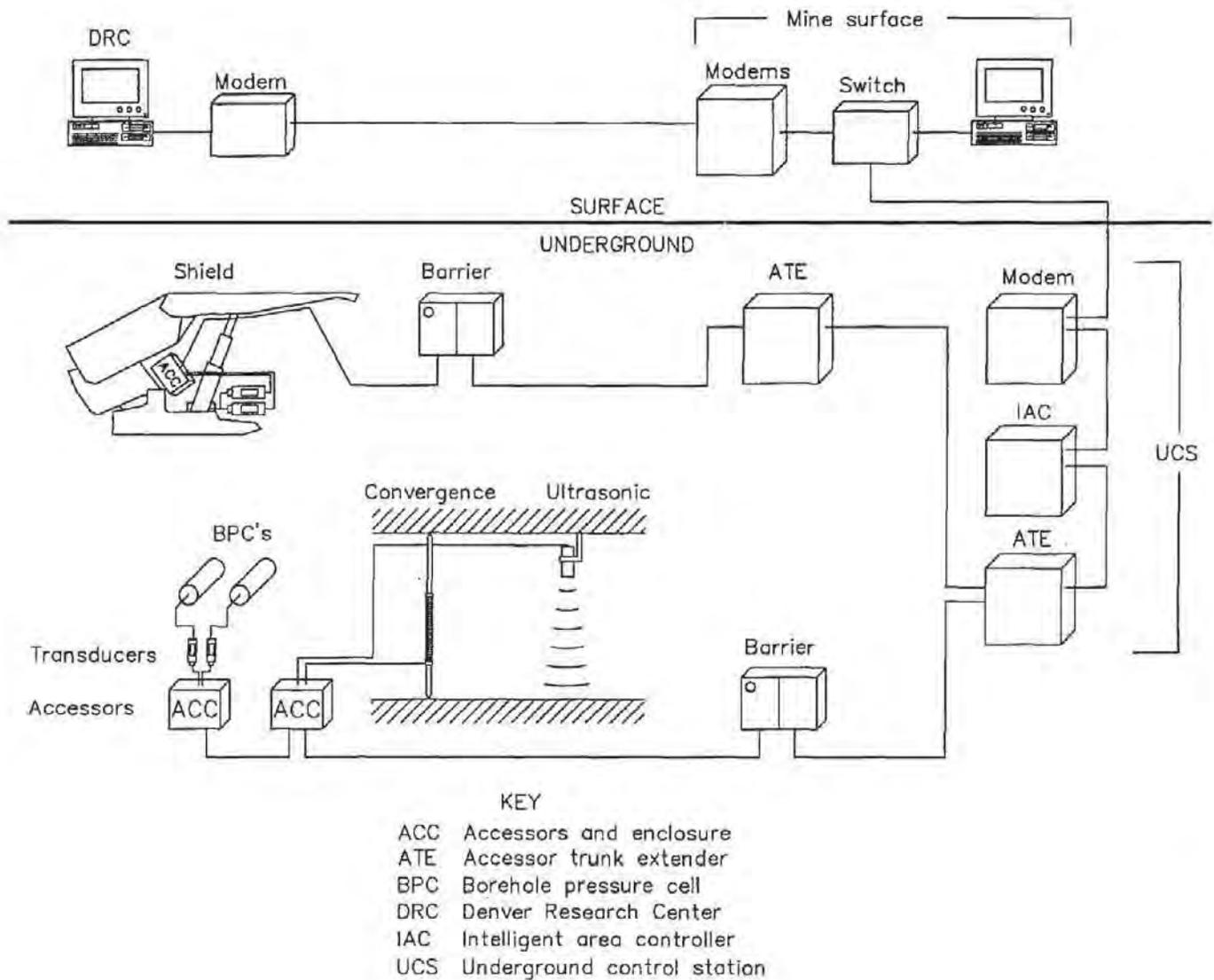
Figure 1.—Schematic of underground monitoring system instrumentation network.

KEY

ACC   Accessors and enclosure
ATE   Accessor trunk extender
BPC   Borehole pressure cell
DRC   Denver Research Center
IAC   Intelligent area controller
UCS   Underground control station

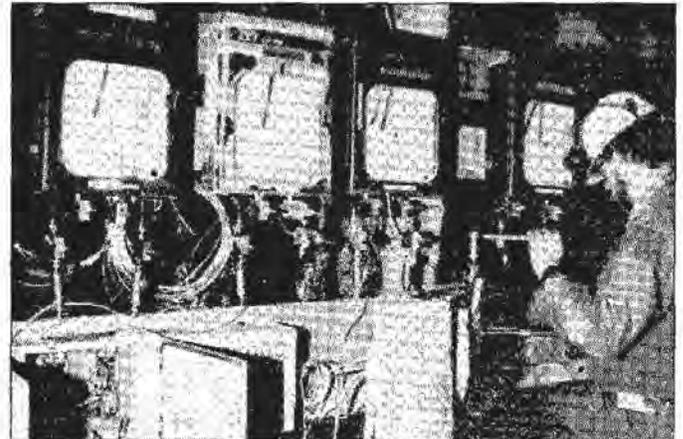Figure 2.—Main computer control station at the Denver Research Center.

Figure 3.—Gate road instrumentation site showing accessors, transducers, and chart recorders.

that supply power to the accessors and sensors, and transmit bidirectional digital information. Each accessor is individually addressed to permit communication with specific instruments or sensors.

Since all instrumentation sites were eventually located in return airways, the trunk cables along the longwall face and to the instrumentation sites were connected through power barriers that limit both voltage and current to satisfy MSHA permissibility requirements. Limiting the power to each trunk line reduced the number of instruments that could be monitored on a single trunk cable. Consequently, separate trunk cables were required to monitor each test site and the longwall face.

Various geotechnical sensors and instruments (pressure transducers, convergence meters, position transducers, and ultrasonic distance meters) were tested for compatibility with the system. The different sensors are compatible with the monitoring system, using both currently available and custom-designed accessors. In general, the sensors are powered by the trunk line (24 V in fresh air, 14 V in permissible areas) and provide either a voltage or current signal that is converted to 8-bit digital form by the accessor. Sensors being considered for use underground should be durable, have low power consumption, and be classified as permissible. Results from various instrument and sensor types are described later.

MINE DEMONSTRATION

Figure 4 shows a layout of the Colorado mine and the general locations of the monitoring system components and gate road instrumentation sites. Figure 5 shows the barrier pillar test area in one of the two Utah mines.

The instrumentation plans were designed to continuously monitor ground behavior during the high-speed extraction of successive longwall panels under different geologic conditions and different pillar arrangements.
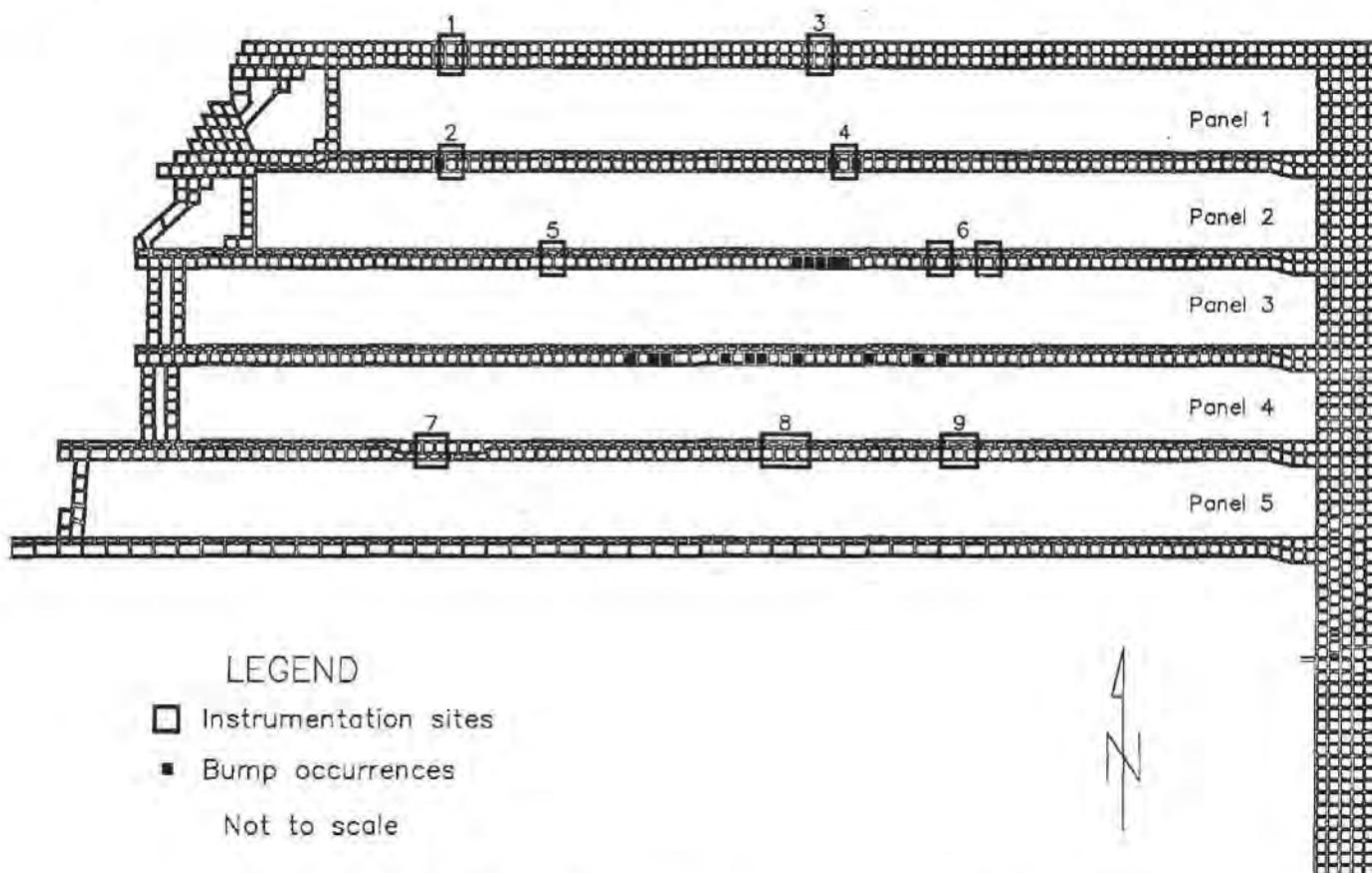

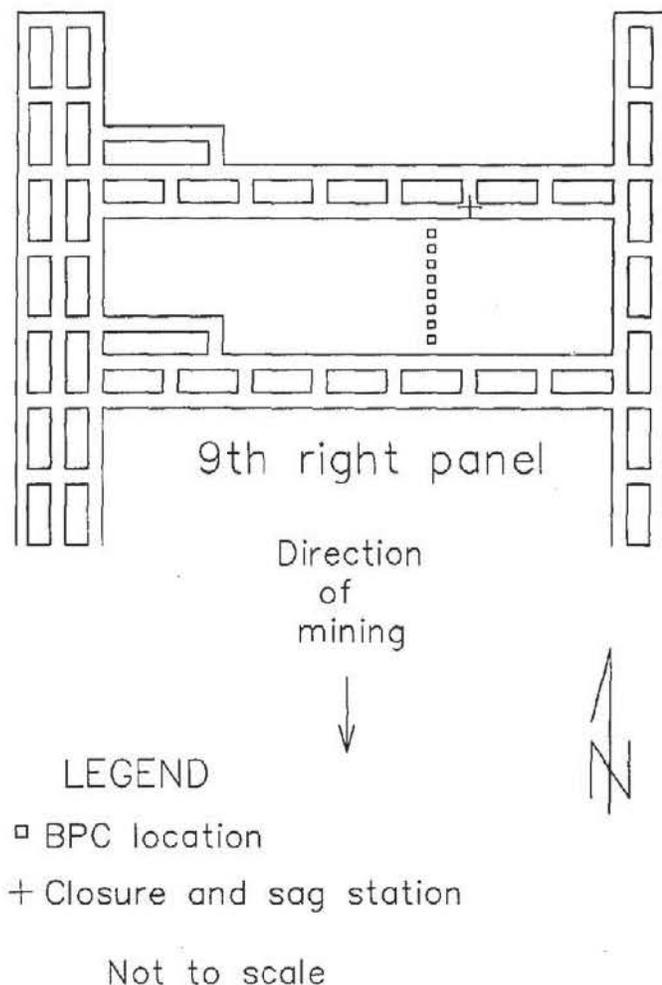Figure 4.—General mine layout at the Colorado longwall mine.

9th right panel

Direction
of
mining

↓

LEGEND

□ BPC location

+ Closure and sag station

Not to scale

Figure 5.—Layout of barrier pillar test area in a Utah mine.

At the Colorado mine, data have been monitored continuously throughout panels 1 through 5 mining. A total of nine gate road instrumentation sites have been monitored during the extraction of the five longwall panels. Shield-leg pressure data from the longwall faces were collected to analyze shield loading behavior along the longwall face, relative pressure behavior between adjacent shields, and near-tailgate loading related to observed caving conditions. Data from the underground instrumentation network were continuously transmitted via phone modem to computers located at the mine surface and the main control station at the DRC mine monitoring laboratory.

The field site at the Utah mine was instrumented to characterize load transfer to the barrier pillar and bleeder system during longwall mining. No shields were connected to the monitoring network at the Utah mines. Data from

the underground test area were transmitted through the mine's monitoring network to the mine surface, where the data were collected and stored on the mine computer. The data were not transmitted directly to the DRC monitoring laboratory (5).

SHIELD INSTRUMENTATION

Figure 6 shows the location of monitored shields for each of the five panels in the Colorado longwall mine. Each of the longwall panels were about 195 m (640 ft) wide by 3,050 m (10,000 ft) long and had approximately 130 shields along each face. The location of monitored shields varied from panel to panel to evaluate the influence on shield pressure from the cycling operations of neighboring shields and to assess the pressure changes along the longwall face. The monitored shield concentration near the tailgate was increased as subsequent panels were mined to better define the shield pressure response to tailgate ground control conditions and near-tailgate roof caving behavior.

GATE ROAD INSTRUMENTATION

Pressure transducers were attached to hydraulic borehole pressure cells (BPC's) installed in the gate road structures at the various instrumentation sites. Convergence rods and position transducers were also installed to measure entry closure and strata movements when the respective longwall faces were near the various test areas. Initially, mechanical chart recorders to measure pressure were installed along with the monitoring system pressure sensor components to verify the data obtained from the monitoring system. These were discontinued when it became evident that the monitoring system provided superior data collection accuracy, reliability, and analysis capabilities.

SYSTEM RELIABILITY

An uninterrupted flow of data is crucial for conducting trend analyses and correlating monitored data with field observations. Special modifications were made to the equipment to ensure system reliability, such as encasing the trunk cable on the longwall face in reinforced hose, fabricating custom enclosures for the components on the longwall face, relocating accessor enclosures to less hazardous areas on the lemniscate assembly of the shields, upgrading and eliminating wiring connectors, and applying waterproofing coatings to accessor cards.

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Headgate   Tailgate

Panel 1

Panel 2

Panel 3

Panel 4

Panel 5

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1   10      30      50      70      90      110     130
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Shield Numbers

KEY

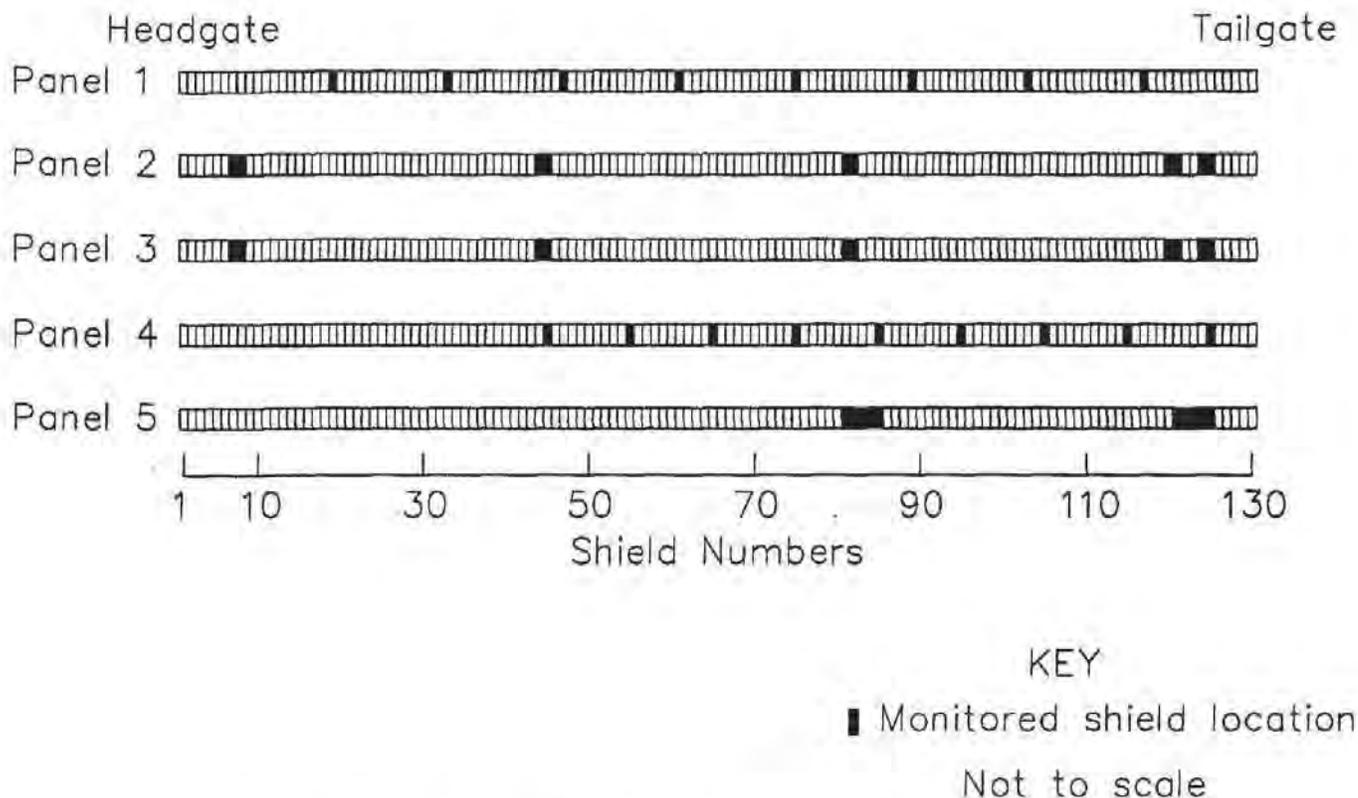▐ Monitored shield location

Not to scale

Figure 6.—Shield monitor locations for panels 1 through 5 at the Colorado longwall mine.

Overall reliability of the monitoring system, including downtime from both external sources (telephone and power) and internal sources (cables, components, and sensors), is approximately 85%. Data collection reliability of the BPC, convergence, and roof sag instrumentation sites, which are located away from the moving machinery in the active face areas, has generally exceeded 90%.

DATA PROCESSING AND EVALUATION

The continuous evaluation and management of ground control hazards associated with high-production mechanized longwall mining depends on the ability to monitor, process, and analyze geotechnical data in real-time. This section will discuss techniques developed for managing and analyzing the large quantities of information supplied by the monitoring network.

The processing and analysis operations have been performed using a variety of commercial and custom software. Figure 7 illustrates the general sequence of data management and analysis. The data collected from the underground instrumentation network are combined with other pertinent information, such as face position and geologic conditions, and analyzed using various techniques.

An advantage provided by the automated monitoring systems over conventional data collection methods is the real-time display and conversion of sensor data to engineering units, which permits timely viewing by the mine engineering and operations staff. Significant or anomalous ground behavior changes can be rapidly identified to alert the mine operator in sufficient time to implement any necessary remedial action. With manual data collection techniques (mechanical recorders, dataloggers, etc.), the data records must physically be collected from the measurement site (retrieving charts and/or storage modules, manually reading instruments, taking measurements, etc.), digitized, and inputted to the computer (or manually plotted) before analysis can begin. With the automated
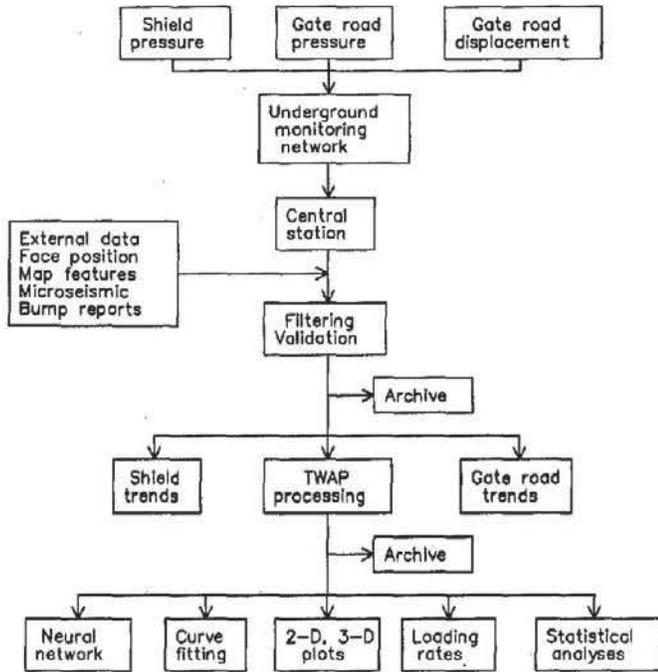
Figure 7.—Data management flowchart. TWAP = time-weighted-average pressure.

data collection system, large quantities of information and data are collected and processed automatically and continuously.

Management of the monitored data consisted of evaluation of the quality of the data through inspections of trend plots, conversion of the binary data to formats more suitable for analysis, and archiving of the data for future use. In addition, external data were digitized to enable inclusion of geologic data, bump occurrences, and longwall face positions into the analyses.

DATA MANAGEMENT SOFTWARE

The main control station computer at the DRC mine monitoring laboratory and the secondary computer system at the mine surface provide a permanent record of the monitored data as stored binary files. Because of the many pressure changes that occur during shield cycling activities, data files for 1 day occupy approximately 2.5 megabytes of disk space. Managing the large volume of shield pressure data required custom software routines to automate the data processing and editing functions.

Data management primarily involves reducing data file size to minimize data storage space requirements and to facilitate more rapid data processing during subsequent analysis procedures. Under normal operating conditions, the shield-leg pressure data have continual small pressure changes, approximately 0.1 to 1 MPa (14.5 to 145 psi),

owing to the shield operation characteristics. Data file size is reduced by ignoring pressure changes less than 0.28 MPa (40 psi).[4] Additionally, periods of sensor and/or monitoring system communication interruption of less than 1 min are also eliminated from the data file storage. The resulting data files occupy only about 10% of the original file storage space. The file size is further reduced for storage using commercial data compression software.

Most of the analysis programs require input data in the form of text files, listing the data in engineering units for selected instruments at specific time intervals. Custom software was written to convert the binary data files into an appropriate format, and a commercial spreadsheet was also used to reformat the data and to combine the monitored data with external data, such as face positions. Data management also involved digitizing mine layout and geologic maps to generate base maps for plotting analysis results.

DATA DISPLAY CAPABILITIES

The monitoring system software package provides graphical displays of data in two formats, real-time and trend, for rapid visual analysis. Real-time displays access the monitored data directly and are updated during each scan interval. The color graphics displays depict data in either numeric form or as bar graphs and can be customized by the operator. The trend displays access data files stored on computer disk and permit examining trends from any prior monitoring period.

The capabilities for processing and displaying geotechnical data are best demonstrated by examples. Real-time displays of shield pressure data illustrate some of the parameters being considered for ground control applications. Figure 8, an actual display of shield pressure data from panel 2, shows shield-leg pressures on all eight monitored shields as bars and numeric values (figure 8A), and trends of the preceding 30-min interval (figure 8B). Examination of this shield data display provides information on shield-leg pressure magnitude and uniformity, rate of pressure increase, and pressure distribution along the face. Once the operator is familiar with the "normal" appearance of the display and shield pressure profiles, any unusual conditions, such as excessive or unequal pressures, can be easily identified. The continuously updated trends shown in figure 8B provide plots of shield pressure behavior; the rate and uniformity of shield cycling and the relative sequence of cycling for all monitored shields can be readily observed (6). For example, referring to the shield 44 trend plot in figure 8B, the unchanging low

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[4]0.28 MPa (40 psi) corresponds to one digitizing interval of the monitoring system using 0 to 70-MPa (0 to 10,000-psi) pressure sensors.
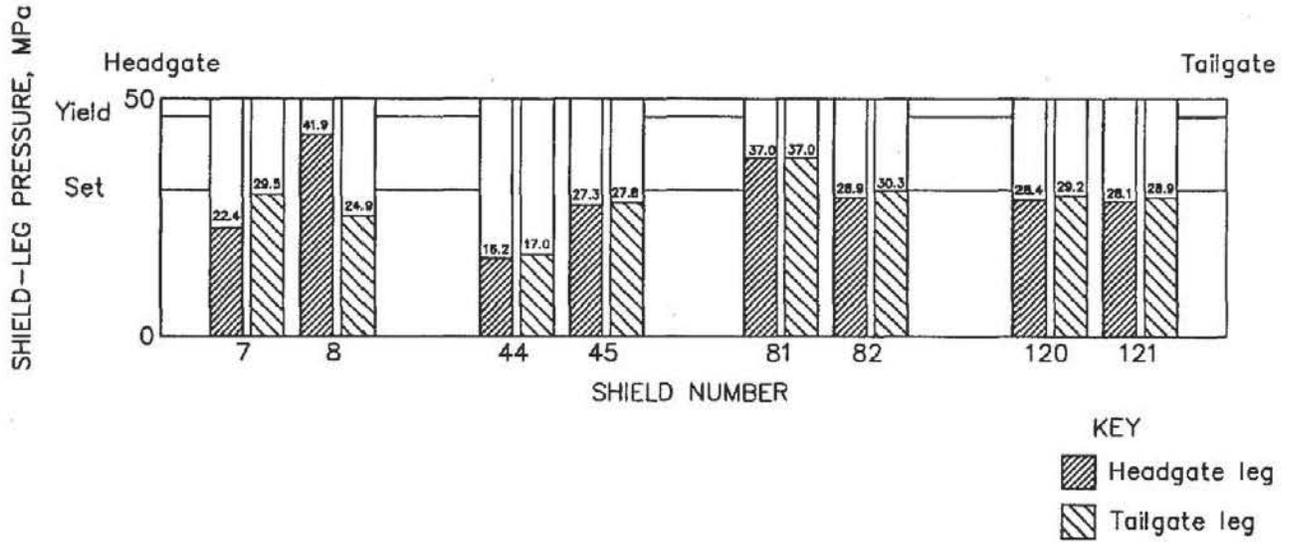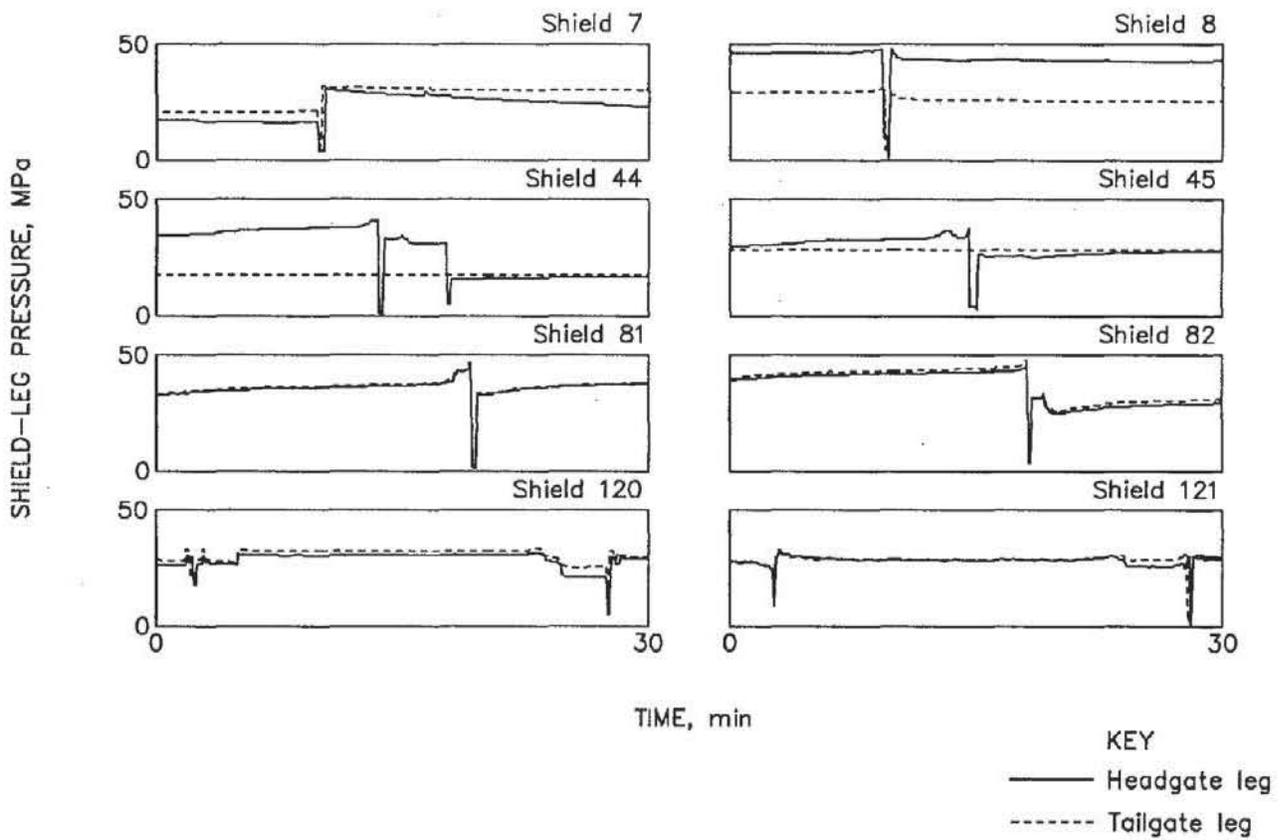
Figure 8.—Display of real-time shield data from panel 2. *A*, Bar graph display with shield-leg pressures. *B*, 30-min trend display.

pressure on the tailgate leg that does not appear to cycle along with the headgate leg could indicate a malfunctioning monitoring system component (sensor or accessor). Again, referring to figure 8B, the trend plot for shield 8 indicates uneven leg pressures which may indicate either malfunctioning shield operation or monitoring system components.

Typical shield loading variations during a production shift are shown in figure 9 (7). The time scale of the trend displays can be easily varied to examine specific

sensor information during any specified time interval. The trend plots are used to evaluate unusual loading conditions that can be examined in greater detail. In addition, the quality of the data can be assessed by identifying abnormal data values caused by malfunctioning instruments, sensors, or other equipment. To identify abnormal data, the operator looks for large differences in headgate versus tailgate leg pressures, unchanging shield pressures in one shield leg during obvious production periods, etc.
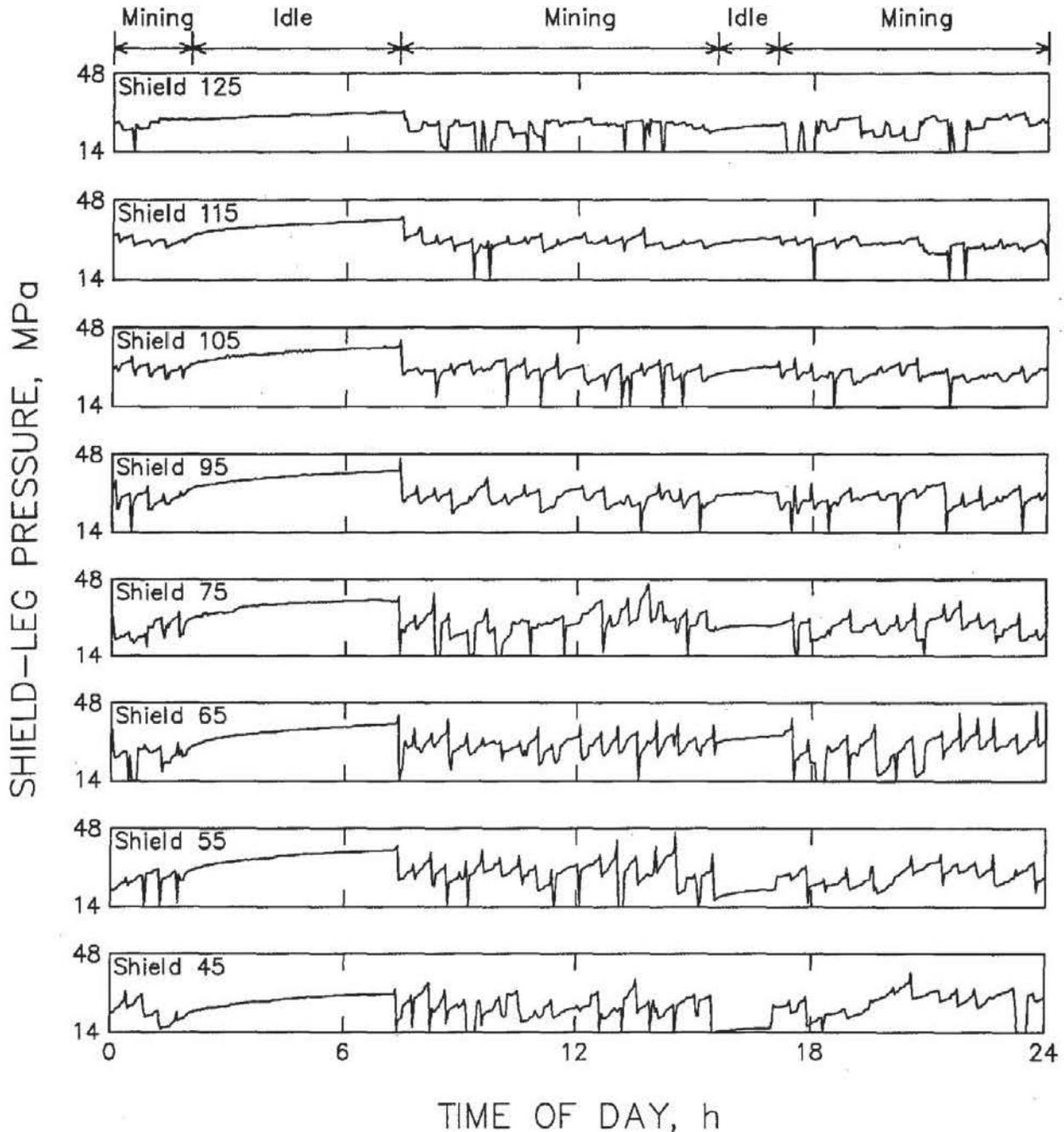
Figure 9.—Shield load variations during a production shift.

DATA ANALYSIS SOFTWARE

Shield data analysis has been primarily concerned with evaluating shield-leg pressure behavior using various parameters calculated from individual shield cycles. Shield data files, obtained from the system software, are processed using custom software to determine the time-weighted-average pressure (TWAP), setting pressure (SP), cycle length (CL), and maximum pressure (MP) for each shield cycle (1). Shield data analysis tasks have been handled primarily by a commercial spreadsheet program. Text files containing the shield TWAP information are combined with face position information from the mine production reports and other shield cycle information to evaluate periodic shield loading conditions and load distributions. The TWAP information is compared to the SP and CL values to evaluate the average load changes experienced by the shields during each loading cycle. To provide a consistent basis for comparison, the TWAP data are further processed to remove the effects of long cycle times, low setting pressures, and other conditions associated with operating procedures, rather than changes in ground conditions.

Gate road pressure and strata movement data are also imported into the spreadsheets to evaluate pillar yielding, load transfer behavior, mine roof stability, and entry convergence relative to longwall face position. Several utility programs were developed to improve the efficiency of data importing, editing, and calculation steps. The spreadsheet data are also used to further process and graphically display the data to assist in analysis and presentation.

Additional commercial software includes programs to plot two-dimensional data sets and generate surfaces and contours of three-dimensional data sets. The three-dimensional plots are being used to examine the relationship between high shield pressures, local geological features, and zones of ground control problems. A sample three-dimensional plot, shown in figure 10, illustrates shield TWAP results for panels 2 and 3. In general, the data reveal higher shield pressures toward the tailgate end of the longwall faces.
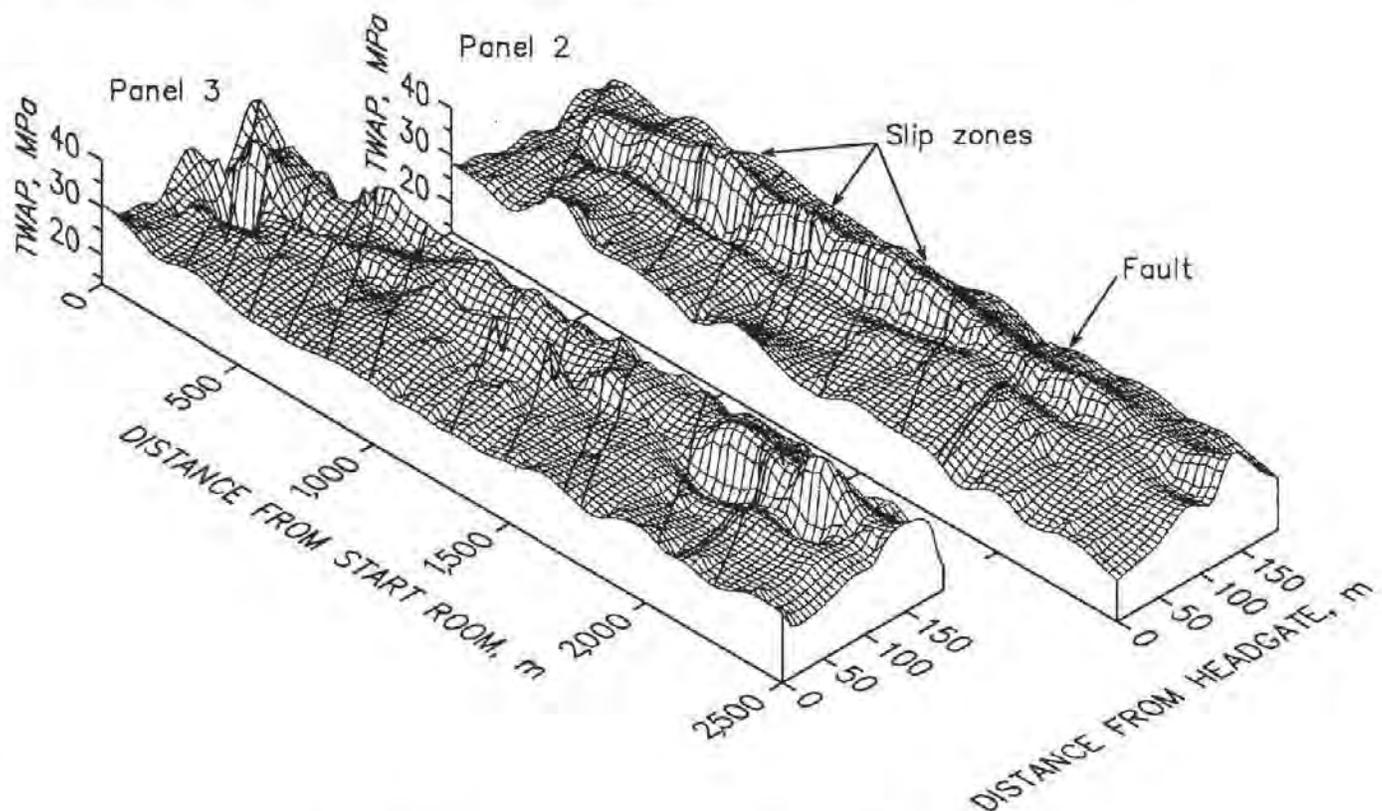

Figure 10.—Comparison of panels 2 and 3 TWAP results with geologic slip zones.

EVALUATION OF GROUND CONDITIONS

The detection and management of ground control hazards associated with high-speed mechanized longwall mining requires real-time monitoring and analysis of geotechnical data combined with a detailed knowledge of the geostructural conditions around the longwall panels. The geotechnical data alone are insufficient to anticipate ground control problems. Geostructural characteristics of the mine site play a significant role in determining ground stability and need to be evaluated along with the geotechnical information (7).

Data from the monitoring system network are analyzed to evaluate rock mass behavior during longwall panel mining, with particular emphasis placed on comparing data patterns to observed ground conditions and local geologic settings. Ground conditions at various locations around the longwall panels were investigated through a review of sensor and site data, and in-mine observations. A typical ground control hazard evaluation map was developed, as shown in figure 11 (7). The hazard map superimposes contour plots of shield TWAP results for panels 2 and 3
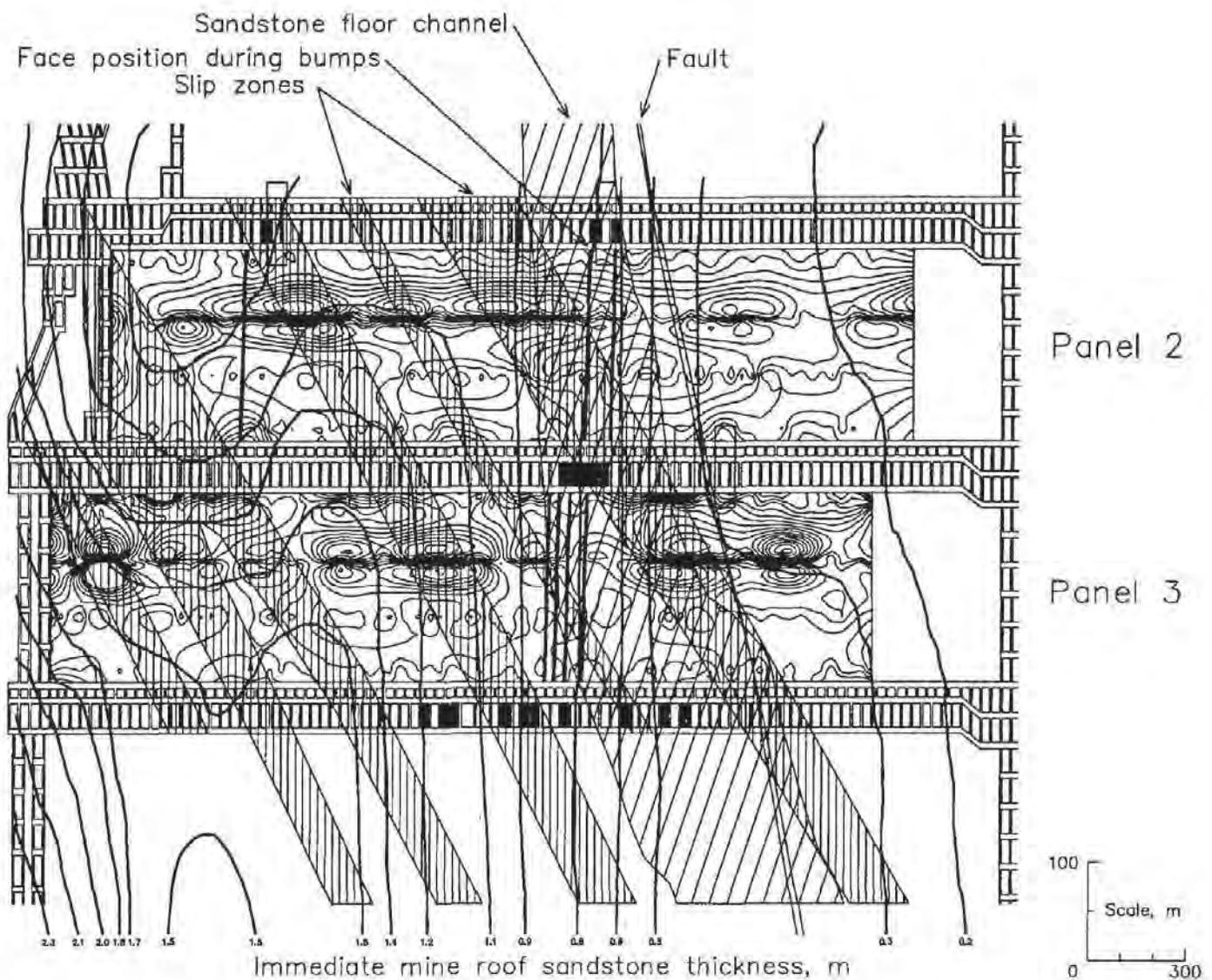

Figure 11.—Ground control hazard evaluation map showing geology, bump locations, and processed shield TWAP data.

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along with locations of geologic slip zones and an isopach of the sandstone member thickness in the immediate mine roof. Based on discussions with mine personnel, the local geologic conditions and roof member structure were the most important parameters affecting gate road ground stability. This type of plot, using monitoring system results along with geologic information, provided the mine operator with information to evaluate anomalous pressure behavior associated with specific geostructural conditions. The hazard map, once developed, can be updated in near real-time with monitoring system results for rapid assessment by mine personnel. Appropriate ground control procedures, such as selecting stress control methods or alternative support types for expected recurring problem areas, can then be implemented if necessary.

The following discussion provides additional examples of near real-time data collection, analysis, and results to demonstrate the capabilities and application of the monitoring system to specific ground control events.

GATE ROAD PILLAR AND STRATA BEHAVIOR

Analysis of BPC data is most readily accomplished through examination of the trend plots. Figure 12 is a plot of yield pillar pressure cell readings at site 4 (location of site 4 is noted in figure 4) over a 4-day period as the panel 1 face mined to a position approximately 122 m (400 ft) past the pillar site. The data plotted in figure 12 illustrate progressive pressure decrease (possible pillar yielding) of the pillar edges (cells 1 and 3) coincident with a pressure

Figure 12.—Yield pillar pressure cell results. A, General mine layout showing cell location. Yield pillar width = 10.7 m (35 ft); stiff pillar width = 24 m (80 ft). B, BPC pressure results.

increase at the center of the pillar (cell 2). Also, the figure shows an apparent load transfer to the adjacent stiff pillar (cell 4) while pressures were dropping on the yield pillar. All of the pressure and load transfer data are transmitted continuously to the mine surface for rapid assessment by mine engineering and operations personnel.

Other information such as entry closure and roof-bed separation is demonstrated through monitoring system results from the barrier pillar test area at the Utah mine. Figures 13 and 14 illustrate strata movement results during longwall mining operations as the longwall face mined away from the barrier pillar. Rates of closure and roof-bed separation (indicators of changing ground stability) were continually monitored and displayed for the mine operations personnel. At this instrumentation site, no significant ground movement or control problems were encountered. The data are merely presented to illustrate the additional capabilities with various sensors.
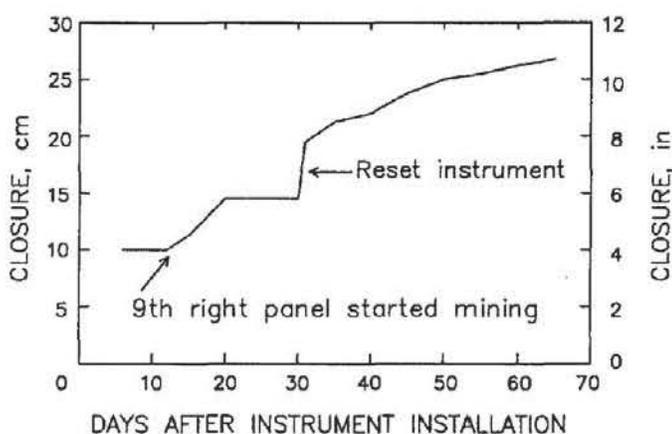

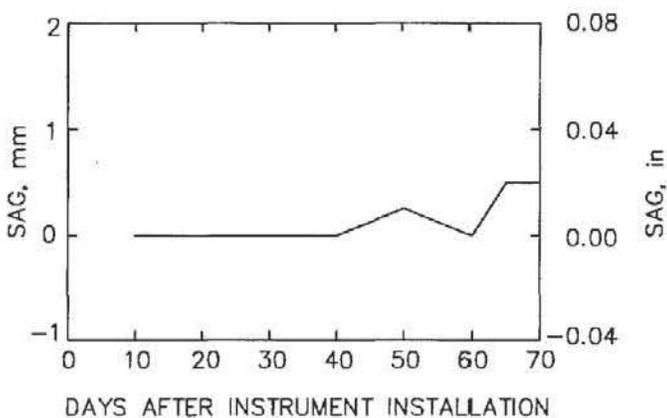Figure 13.—Convergence results.

Figure 14.—Roof-bed separation results.

SHIELD LOADING BEHAVIOR

Shield loading analysis has primarily involved identifying anomalous patterns of individual shield cycles. Trends of the shield pressure data have been used to evaluate shield and face loading conditions (6). The first example of anomalous shield-leg pressure increases occurred while monitoring the initial caving of panel 2. The leg pressures on the four midpanel shields increased rapidly to yield pressure during two consecutive cycles. Figure 15, a 16-h detail plot of these cycles, shows the rapid pressure increases that occurred in midcycle (about 2.7 h after the start of the plot) and, once again, 1.4 h later. At that time, another large pressure increase occurred. According to mine personnel working at the face, a major roof cave occurred as noted on figure 15 approximately 2 h after the second major pressure increase (6).

Rapid pressure increases were also observed on several occasions that coincided with rapid tailgate floor heaves immediately outby the face during panels 2, 3, and 4 mining. Figure 16, a plot of both shield and pillar pressures during a bump at the Colorado longwall mine, displays pressure trend information from the panel 2 shields and from BPC's installed in the tailgate of panel 2 at site 2. Shields 120 and 121, within 12.1 m (40 ft) of the tailgate edge of panel 2, experienced sharp pressure increases in midcycle. The shield pressure increase coincides precisely with similar pressure increases in the BPC's installed in the tailgate stiff pillar at site 2. Approximately 1 m (3 ft) of floor heave occurred adjacent to the tailgate end of the panel 2 longwall face at approximately the same time as the rapid pressure increases in the shields and the stiff pillar. Shields 81 and 82 on the panel 2 face showed no corresponding pressure increase, suggesting that the influence of this tailgate event extended no more than about 61 m (200 ft) into the panel.

Additional tailgate ground control events during panels 2, 3, and 4 (locations shown in figure 4) coincided with rapid shield-leg pressure increases on the near-tailgate shields. Rapid pressure increases of 1.4 to 13.8 MPa (200 to 2,000 psi) occurred in the shield legs in only one scan interval, less than 6 s. Normally, the shield-leg pressure increases by approximately 3.4 to 13.8 MPa (500 to 2,000 psi) over the entire shield cycle, almost 30 min. No corresponding pressure increases were observed on the shields at the center or headgate end of the panel during any of the near-tailgate events. The tailgate events typically involved pillar sloughage, extensive floor heave, and mine roof problems for a distance up to 45.7 m (150 ft) outby the face.
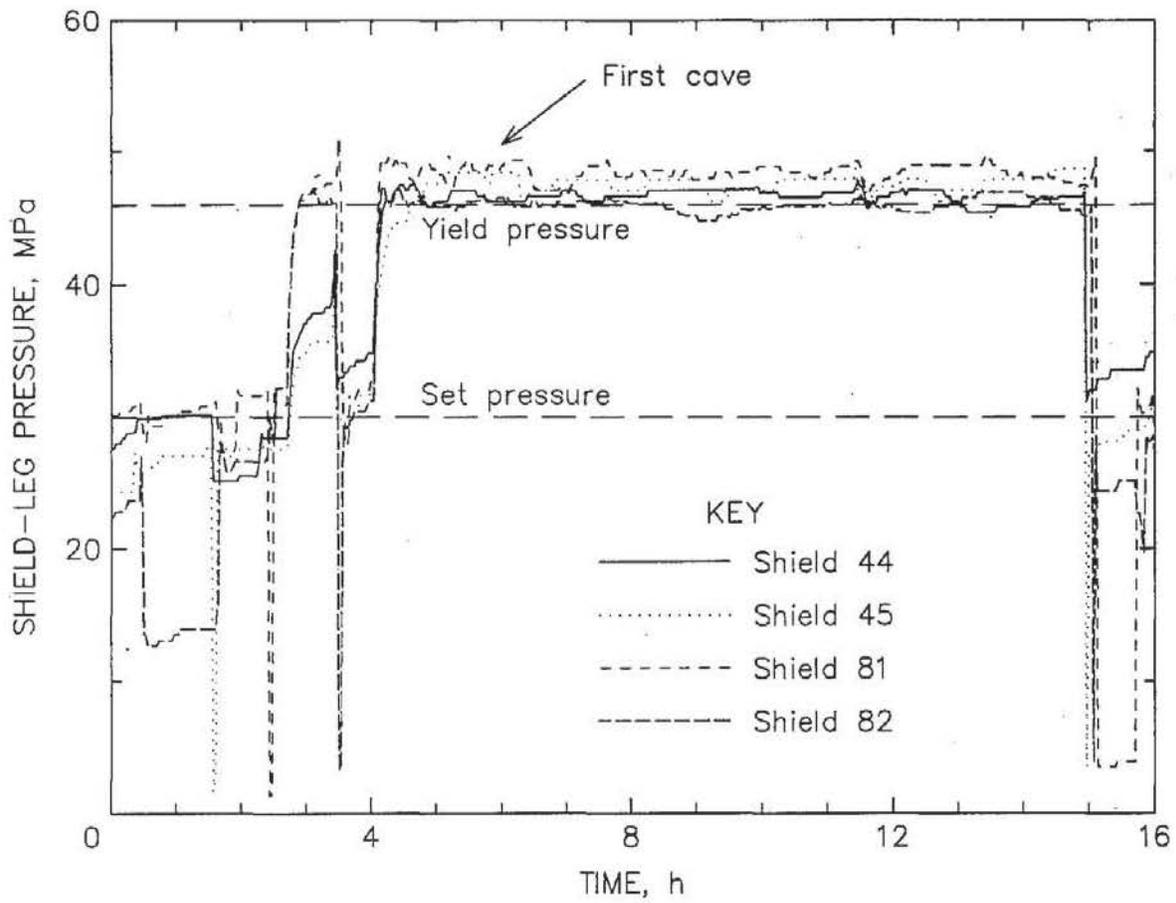
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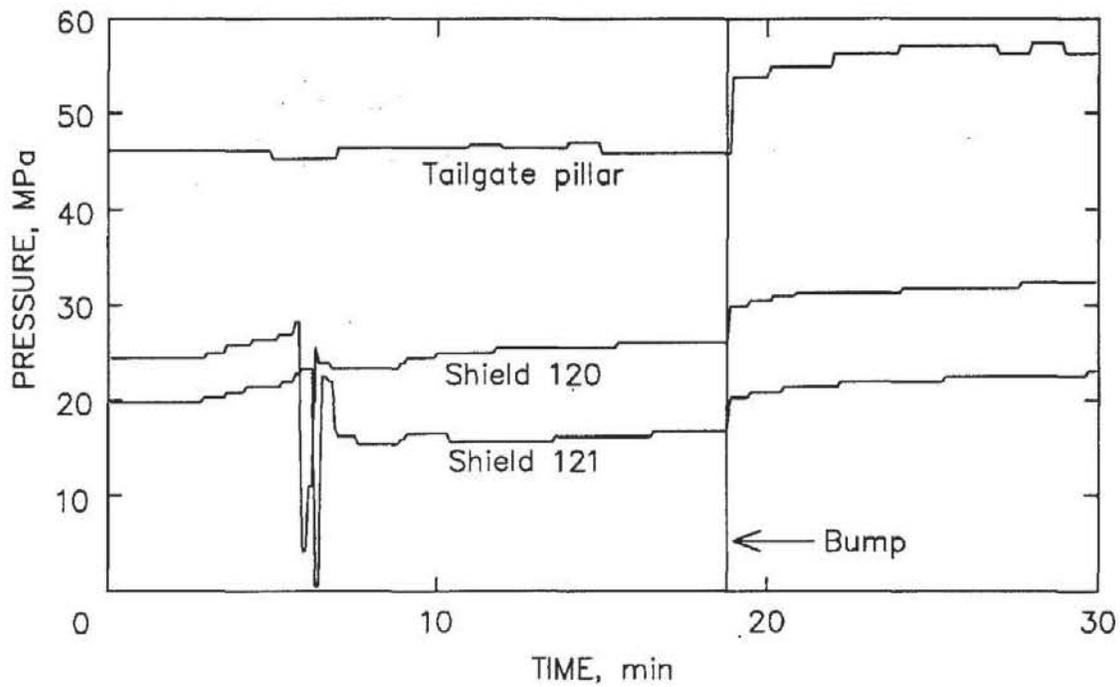Figure 15.—Shield-leg pressure results during panel 2 first cave.

Figure 16.—Simultaneous shield and pillar pressure increases.

SUMMARY AND CONCLUSIONS

The development of an automated monitoring system for coal mine ground control evaluation has greatly improved data quality, access time, and speed of analysis over conventional monitoring methods. Continuous real-time acquisition of underground mine structure information (strata movement and pressure), coupled with automated processing and evaluation of ground conditions, has been demonstrated and has proved valuable in assessing mine structure behavior during longwall production mining. Combining mine structural behavior data with other information, such as local geological conditions, within an automated monitoring and data processing system has provided information on stress transfer and pressure buildup associated with several ground control events. Shield-leg and ground pressure changes, along with strata movement monitoring results, have been used to identify and assess abnormal changes in ground conditions. Real-time stress transfer information, coupled with mine opening convergence and structure deformation information, provides the potential for rapidly and effectively evaluating underground conditions as mining progresses. The monitoring system information, when combined with direct observations by mine personnel, permits a more rapid and complete near real-time evaluation of face area hazardous conditions. As a result, the mine operator can make critical decisions related to coal mine ground control with more information in a more timely manner.

ACKNOWLEDGMENTS

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New Technology for Longwall Ground Control

Proceedings: U.S. Bureau of Mines Technology Transfer Seminar

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Richard C. Repsher, and Catherine L. Simon

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES

Cover Photograph: The U.S. Bureau of Mines has developed highly practical technologies for
maintaining effective ground control in the hazardous tailgate entries of longwall
mining systems, which will significantly improve the safety of the Nation's
underground mineworkers. *(Photo: Alan A. Campoli, Pittsburgh Research Center,
U.S. Bureau of Mines)*