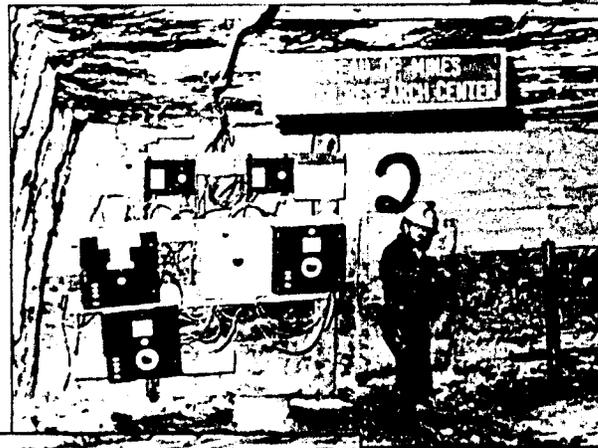PB95-147930

Computer-Assisted Ground Control Management System

By David P. Conover, John P. McDonnell, and Kanaan Hanna

United States Department of the Interior

Bureau of Mines

U.S. Department of the Interior
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The U.S. Bureau of Mines (USBM) has developed a computer-assisted Ground Control Management System (GCMS) for near real-time evaluation of underground coal mine ground conditions. The GCMS combines existing mine monitoring system and sensor technology with automated computer analysis techniques to enhance the acquisition, analysis, and display of geostructural data. The GCMS, which combines mine structure data with other information, such as geologic conditions and mine layout, has provided information on mining-induced stress transfer and pressure buildup associated with several ground control events.

The GCMS collects and analyzes shield-leg pressure, ground pressure, and strata movement data to evaluate the structural behavior of an active western U.S. longwall coal mine. Field data are transmitted over a dedicated phone line to the USBM Denver Research Center (DRC) mine monitoring laboratory, 240 km (1 miles) from the mine site.

Real-time collection, processing, and analysis of mine structure and shield pressure information has proven to be an effective method for assessing near-face ground conditions while mining progresses. The GCMS provides the mine operator with information to rapidly identify and manage potentially hazardous ground conditions while mining is in progress.

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

bps	bit per second		min	minute
cm	centimeter		mm	millimeter
ft	foot		MPa	megapascal
ga	gauge		ms	millisecond
h	hour		mt	metric ton
in	inch		mV	millivolt
km	kilometer		psi	pound per square inch
m	meter		s	second
mA	milliampere		st	short ton
Mb	megabyte		V	volt

COMPUTER-ASSISTED GROUND CONTROL MANAGEMENT SYSTEM

By David P. Conover,[1] John P. McDonnell,[1] and Kanaan Hanna[2]

ABSTRACT

The U.S. Bureau of Mines (USBM) has developed a computer-assisted Ground Control Management System (GCMS) for near real-time evaluation of underground coal mine ground conditions. The GCMS combines existing mine-monitoring system and sensor technology with automated computer analysis techniques to enhance the acquisition, analysis, and display of geostructural data. The GCMS, which combines mine structure data with other information, such as geologic conditions and mine layout, has provided information on mining-induced stress transfer and pressure buildup associated with several ground control events.

The GCMS collects and analyzes shield-leg pressure, ground pressure, and strata movement data to evaluate the structural behavior of an active Western U.S. longwall coal mine. Field data are transmitted over a dedicated phone line to the USBM Denver Research Center (DRC) mine monitoring laboratory, 240 km (150 miles) from the mine site.

Real-time collection, processing, and analysis of mine structure and shield pressure information has proved to be an effective method for assessing near-face ground conditions while mining progresses. The GCMS provides the mine operator with information to rapidly identify and manage potentially hazardous ground conditions while mining is in progress.

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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 and support equipment have resulted in increased longwall production and panel retreat rates. Rapidly changing stress conditions that accompany high mining rates challenge mine operators to maintain safe working conditions. Because the longwall face is retreating so quickly, evaluation of ground control problem areas (due to different geologic conditions, as an example) requires more rapid planning.

The design, implementation, and management of ground control systems are difficult due to three conditions: (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 the mine-generated geostructural data and possible control techniques. Controls are often implemented too late to prevent major problems. The U.S. Bureau of Mines (USBM) is conducting research to improve the management of ground control systems by combining minewide monitoring technology with automated analysis techniques. The overall system, termed the Ground Control Management System (GCMS), consists of both hardware (minewide monitoring network and control computers) and software (automated data analysis and display packages) (2).

Advancements in sensor technology and monitoring systems have improved remote acquisition of underground mining information. Minewide monitoring systems are becoming commonplace in U.S. mines and are used by mine personnel to manage many diverse mining activities. Monitoring systems are improving safety and productivity,

and ongoing development is providing additional capabilities and greater flexibility (1, 3-4). Although previous ground control studies (1) have used acquisition systems for data collection, the application of these systems for real-time geotechnical monitoring analysis for ground control planning is not widespread. Real-time acquisition of data, coupled with automated processing, provides important decision-making tools for mine management (3, 5). The general approach taken in evaluating monitoring systems for ground control is to utilize existing monitoring and sensor technology for data collection, storage, and processing. A current trend in monitoring system development is the integration of separate mine-monitoring systems under a central control (1, 3-4). Thus, ground control applications must be compatible with existing systems for maximum benefit.

A goal of this research is the automation of both the acquisition and analysis of ground control information. Data acquisition is accomplished using commercially available monitoring system components and instrumentation. Analysis of data from the GCMS instrumentation network is accomplished using commercially available software packages and custom software routines.

The GCMS instrumentation network was installed in a Colorado coal mine to aid in evaluating ground conditions along a high-production longwall face and surrounding gate road entries. The geostructural data, consisting of pillar, panel, and shield pressure changes and strata movements, are monitored remotely, via phone line, at the mine surface and the DRC mine-monitoring laboratory. Computers linked to the system process the mine structure data and generate graphic displays to permit near real-time detailed evaluation of strata control information.

This report discusses the in-mine application of the GCMS and presents several examples of GCMS results.

GROUND CONTROL MANAGEMENT SYSTEM COMPONENTS

The GCMS instrumentation network was designed to provide real-time ground control information and data from an operating longwall mine for subsequent automated analysis and evaluation tasks. The GCMS also serves 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 or production face

areas are approved by the U.S. Mine Safety and Health Administration (MSHA).

Figure 1 is a schematic of the GCMS network. The system layout was designed to continuously monitor shield loading on the longwall face and ground condition changes (pressure and displacement) at several gate road sites having different pillar configurations. The primary parameters measured were shield-leg pressures along the longwall face and ground pressures in the gate road pillars. Other parameters measured in the gate roads were horizontal ground pressure in the roof, roof-bed displacement, and

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[3]Italic numbers in parentheses refer to items in the list of references preceding the appendix.

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 1.—Schematic diagram of monitoring network.

roof-to-floor convergence. The numbers of sensors, locations of various monitoring system components, and cable routes and lengths were adjusted throughout the monitoring program, as necessary, depending upon the specific instrumentation layout (*1*).

COMPUTER CONTROLS

The main computer control station, shown in figure 2, is located at DRC and currently consists of a Conspec Model 400 Mine Monitoring System[4] computer linked to

various graphics and data-processing computers. Initial research work was conducted using a Conspec Model 200/300 Mine Monitoring System (*1*). The main computer controls communication with the sensors at the mine and displays sensor status. Coupled with the primary computer is a graphics system installed both on a separate computer at DRC and on 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 Model 200/300 Monitoring System, used during mining of panels 1, 2, and 3, provided updated readings from all sensors at 6-s intervals. The data were displayed in real time, processed to remove minor changes, and

stored on computer disk to provide a permanent record. The data were stored using a Conspec proprietary, compressed file format to reduce the storage space requirements. One day's unprocessed data, from the approximately 100 sensors connected to the system, occupied approximately 150,000 bytes of disk space.

The Model 400 Monitoring System, installed during panel 4 mining at the study mine, collects updated readings from the underground sensors at a rate of 0.13 s per sensor and transmits the data, via a dedicated phone line, at 4,800 bps from the mine to DRC. The data are displayed in real time, processed to remove minor changes, and stored on computer disk for permanent record. One day's unprocessed data, from the approximately 100 instruments connected to the Model 400 System at any one time, occupy approximately 2.5 Mb of disk space. The Model 400 System has the capability to monitor up to 15,000 instruments from 7 different mine sites and can support up to 16 remote graphics terminals for displaying and analyzing the geotechnical data. Detailed specifications for the Conspec Model 400 Mine Monitoring System are contained in the appendix.

The mine surface installation consists of two modems, a communication-monitoring switch, and a secondary computer system. The modems control communication between DRC, the mine surface, and the underground control station (UCS). The secondary computer is a complete monitoring control system, which is connected to the monitoring network through a communication-monitoring switch. Under normal circumstances, the monitoring network is controlled from the primary computer at DRC, and the mine surface computer merely monitors the data signals to permit data viewing and backup data storage. If long-distance telephone communication to DRC is interrupted, the monitoring switch enables the mine surface

computer to assume active control of the system to ensure uninterrupted data collection.

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 in close proximity to an available power supply. Figure 3 shows the panel 1 UCS, where the various components were mounted on a timber frame. Subsequently, the UCS components were mounted on a small rubber-tired trailer to expedite relocation of the UCS as successive panels were completed.

Sensors are connected to the GCMS 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 4, 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, which supply power to the accessors and sensors and transmit bidirectional digital information.

Figure 2.—Main control station at DRC.

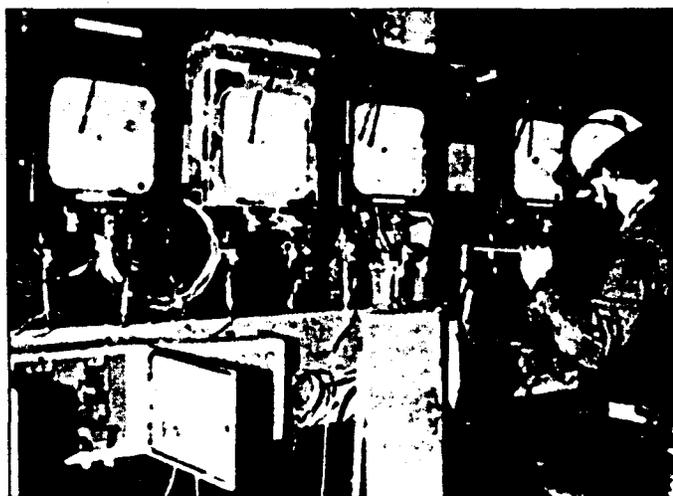Figure 3.—Underground control station.

Figure 4.—Gate road instrumentation site showing accessors, transducers, and chart recorders.

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.

The shield-monitoring installation consisted of a separate metal enclosure, shown in figure 5, which housed the two accessors and two transducers for each monitored shield. The transducers and accessors were located within the enclosure for protection from the harsh environment at the face. The enclosures were mounted either to one shield leg or to the lemniscate assembly. The transducers were connected to the pressure relief valves on both shields using high-pressure stainless steel valves and tubing. Additionally, all trunk cable, from the tailgate end of the face to the outby end of the monorail, was encased in sections of reinforced hose or plastic conduit to minimize cable damage during mining operations. To accommodate shield movement during panel retreat operations, the encased cable was looped between the shields and tied to the shield hydraulic hoses and power cables. In the headgate, the trunk cables were routed along the monorail system to a trunk barrier installed at the outby end of the monorail. Trunk cable, in 76-m (250-ft) long sections, was installed from the outby end of the monorail to the UCS using quick-connect couplers to facilitate cable removal when the monorail was extended during longwall power moves.
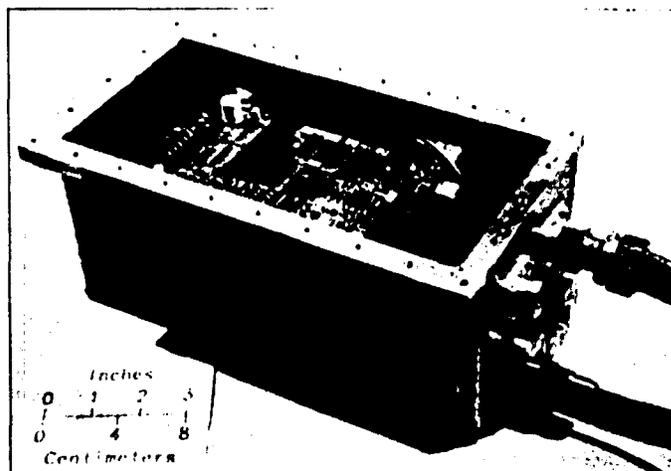
Figure 5.—Custom shield enclosure. A, Open enclosure showing accessor card; B, sealed enclosure.

SENSORS

A wide variety of sensor types are compatible with the GCMS, 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 a current signal that is converted to 8-bit digital form by the accessor. The analog sensor output is digitized at the accessor into an 8-bit word, providing a system resolution of 1 part in 255, or 0.4%. For 0- to 70-MPa (0- to 10,000-psi) pressure transducers, the resolution is 0.28 MPa (40 psi). Deformation sensors, which have typical measurement ranges of 5.1 to

15.2 cm (2 to 6 in), achieved resolutions of 0.02 to 0.06 cm (0.008 to 0.024 in). Each accessor is individually addressed to permit communication with specific instruments or sensors.

Sensors used underground with the GCMS should be durable, have low power consumption, and be classified permissible. Various geotechnical sensors and instruments were tested for compatibility with the system and are described below. Detailed specifications for the sensors are listed in the appendix.

Pressure Transducers

For pressure measurements, T-Hydronics pressure transducers, shown in figure 6, having a 0- to 70-MPa (0- to 10,000-psi) range were used. The sensors are permissible, have low power consumption (2 mA), and are packaged in a rugged stainless steel case. The sensors require a power source in the 10- to 30-V range and produce a linear output voltage in the 0.5- to 5.5-V range. The sensors required a custom accessor to accommodate the unusual output range.

Convergence Meters

For convergence measurements around the longwall face and gate roads, Serata permissible electronic convergence meters were used (figure 7). The meters were connected to accessors, which were modified to supply a 5-V output. The convergence meters have a working range of 12.7 cm (5 in) and can be adjusted in 7.6-cm (3-in) increments for different entry heights. The meters have a resolution of 0.003 cm (0.001 in); however, with the type of accessor cards used, the resolution was reduced to 0.05 cm (0.02 in). Since measured total convergence ranged from 2.5 to 20.3 cm (1 to 8 in), the resolution provided by the monitoring system was considered adequate.

Position Transducers

Roof-bed displacement was monitored using Rayelco linear motion transducers (figure 8), which were connected to stainless steel wires and spring anchors installed in a borehole. The transducers provide a 5.1-cm (2-in) measuring range and a 4- to 20-mA sensor output. The transducers were mounted in a protective enclosure anchored in the borehole collar. A standard accessor was used to connect the sensors to the GCMS, which resulted in a resolution of 0.02 cm (0.008 in).
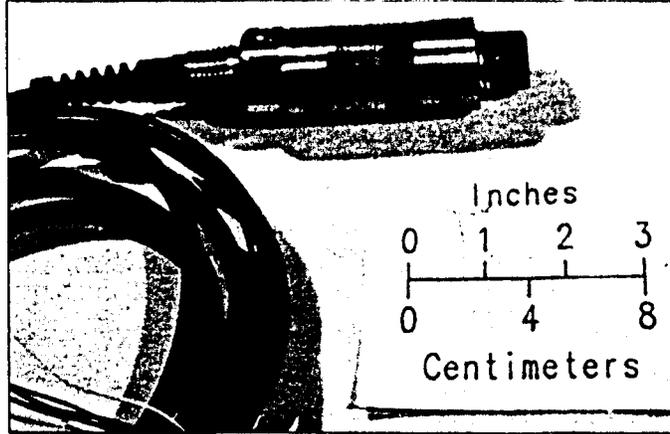

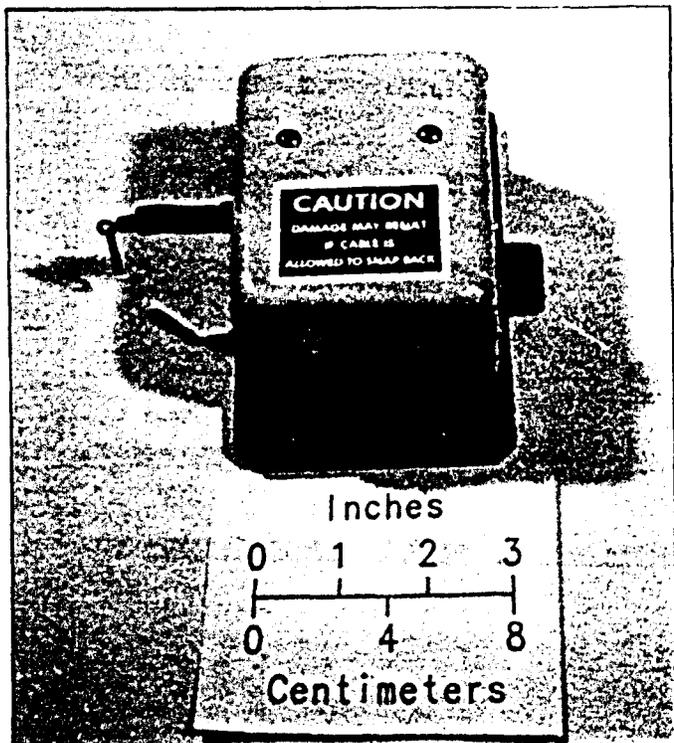Figure 6.—T-Hydronics pressure transducer.

Figure 7.—Serata closure meter.
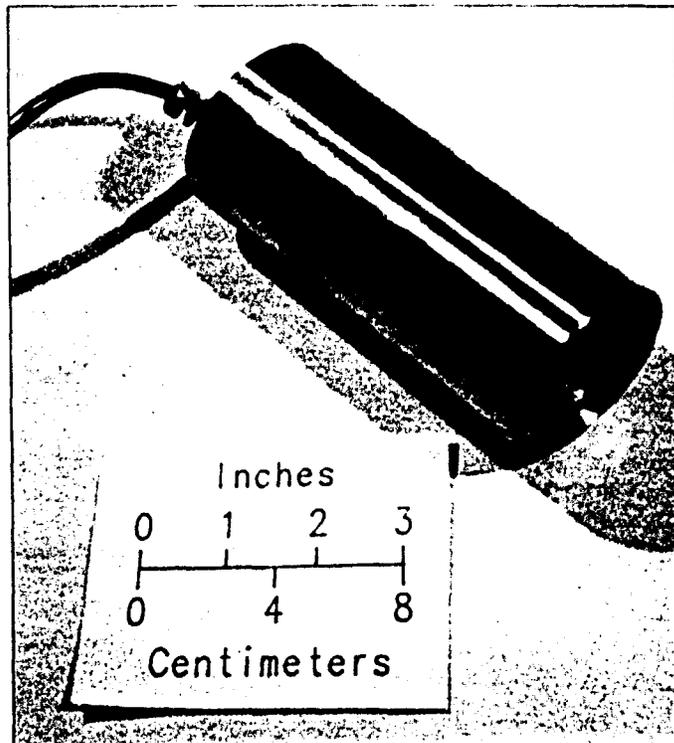
Figure 8.—Rayelco linear motion transducer.

Figure 9.—Lundahl ultrasonic distance meter.

Ultrasonic Distance Meters

Lundahl ultrasonic distance meters, shown in figure 9, were installed in the headgate to monitor gate road roof-to-floor convergence. The meters were not approved for use in permissible mine areas; therefore, measurements were collected only in fresh-air areas. The meters provide a 0- to 5-V signal over a measuring range of 0.3 to 9.1 m (1 to 30 ft). A protective mounting bracket was fabricated to attach the sensors to a roof bolt head for easy installation and relocation.

FIELD STUDY DESCRIPTION

The capabilities of the GCMS have been demonstrated by continuously collecting and evaluating data, in near real time, during the extraction of five consecutive longwall panels. The data have provided insight into shield loading behavior, roof strata caving characteristics, ground pressure redistribution around longwall panels, and ground failure modes.

The GCMS instrumentation network was installed at an underground longwall coal operation in western Colorado (1). Figure 10 shows a layout of the mine and the general locations of the GCMS components and gate road instrumentation sites.

The coal seam in the mine area is about 335 m (1,100 ft) deep and 2.9 m (9.5 ft) thick. The longwall panels are approximately 195 m (640 ft) wide by 3,050 m (10,000 ft) long. Gate road development consists of a three-entry yield-abutment pillar system composed of 5.5-m (18-ft) roadways, a yield pillar about 10.7 m (35 ft) wide adjacent to the headgate, and an abutment pillar about 24.4 m (80 ft) wide adjacent to the tailgate. All of the longwall panels have utilized the same set of Westfalia two-legged shield supports rated at 564-mt (622-st) capacity. The mine's production rate typically exceeds 9,070 mt (10,000 st) in a 10-h shift, which amounts to approximately 12 m (40 ft) of longwall retreat per production shift (2).

INSTRUMENTATION PLAN

The instrumentation plan was designed to continuously monitor ground behavior during the extraction of
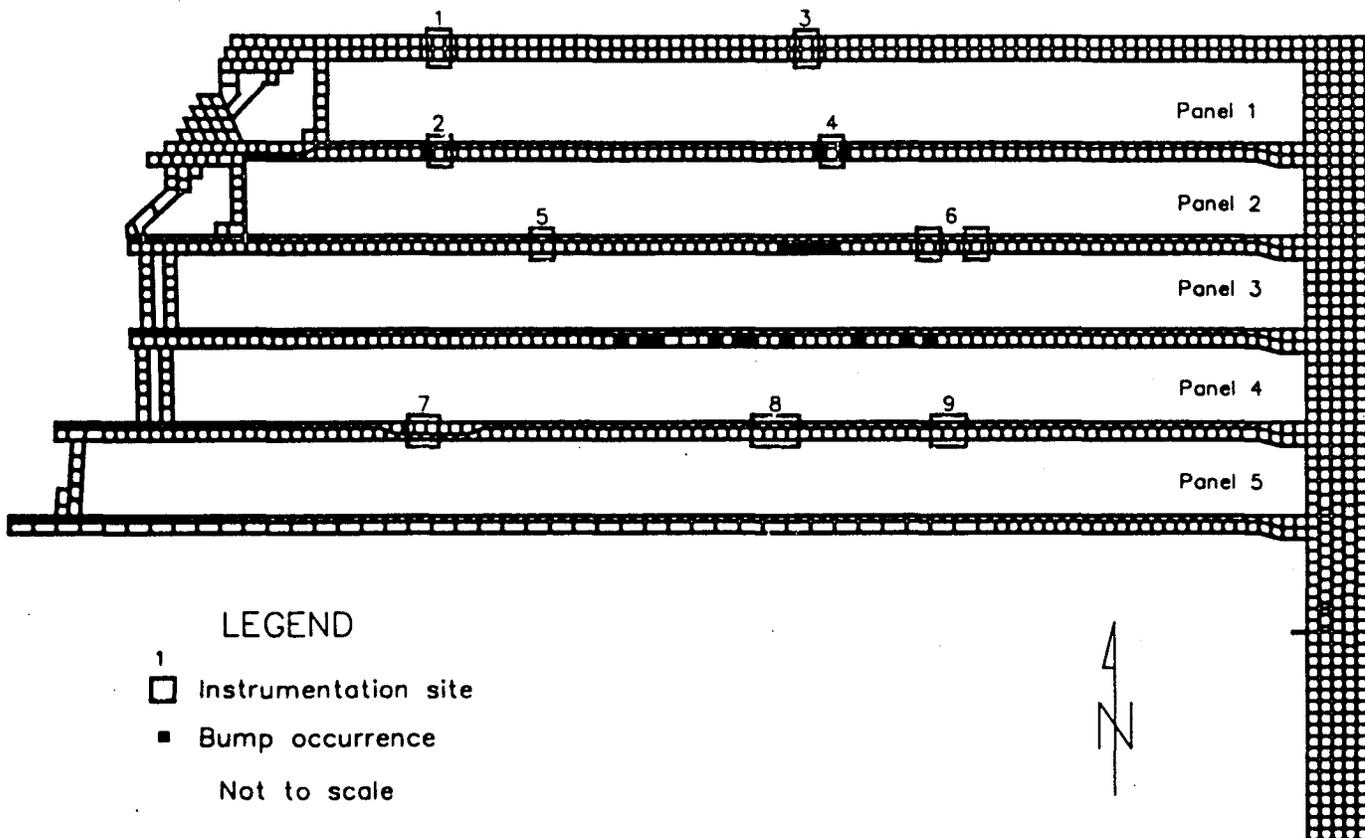
8

Figure 10.—General mine layout.

successive longwall panels under different geologic conditions. Shield-leg pressure data have been monitored continuously throughout the mining of panels 1 through 5. In addition, 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 to the computers located at the mine surface and the main control station at the DRC mine-monitoring laboratory.

Shield Instrumentation

Figure 11 shows the location of instrumented shields for each of the five panels. Each panel had approximately 130 shields along the face. From panel to panel, the configuration of instrumented shields on the face was varied to provide more specific information on shield loading and

strata behavior. For example, during panel 1 mining, transducers were installed on eight shields evenly spaced along the longwall face (shields 19, 33, 47, 61, 75, 89, 103, and 117) (*1*). This arrangement provided shield-leg pressure data across the entire face.

For panel 2, two adjacent shields at four uniformly spaced locations were monitored (shields 7, 8, 44, 45, 81, 82, 120, and 121). This monitoring arrangement was used to evaluate the influence on shield pressure from the cycling operations of neighboring shields. An additional shield (shield 125) was added to the instrumentation plan midway through panel 2 retreat. The additional shield in the tailgate was added to the monitoring network to better define the shield pressure response to tailgate ground control problems and near-tailgate roof caving behavior.

Subsequent configurations provided more insight to the shield loading behavior nearer the tailgate. Panel 3 instrumented shields (7, 8, 44, 45, 81, 82, 120, 121, 124, and 125) provided more complete coverage of the tailgate region, based on the recorded ground control events that occurred during panel 2 mining.

HEADGATE   TAILGATE
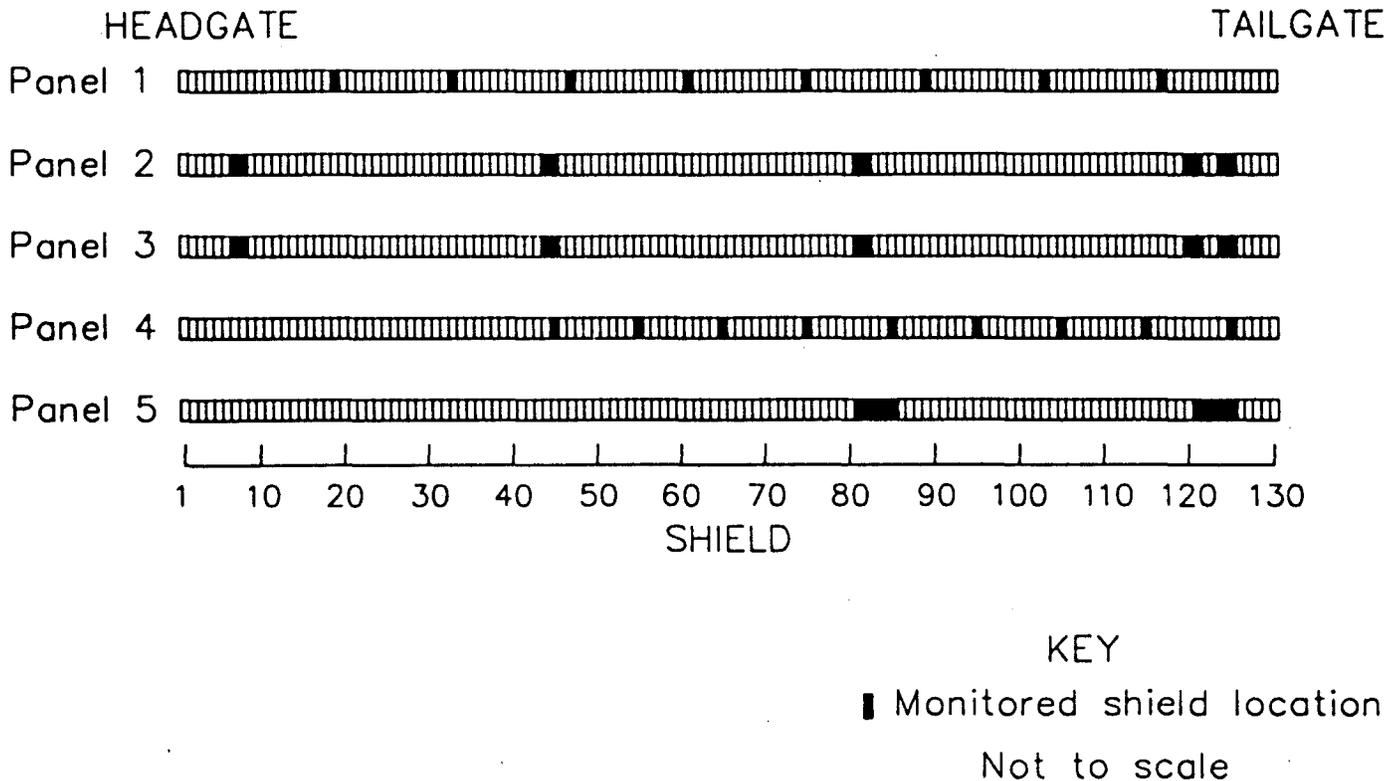

KEY

▌ Monitored shield location

Not to scale

Figure 11.—Shield monitor locations for panels 1-5.

Panel 4 monitoring consisted of nine shields evenly spaced along the face (shields 45, 55, 65, 75, 85, 95, 105, 115, and 125). This arrangement provided more information toward the tailgate portion of the panel because previously monitored panels showed little shield-leg pressure changes on shields near the headgate.

The shields at the study mine are advanced in banks; the even-numbered shields in each bank are moved first, followed by the odd-numbered shields. To evaluate the influence of the move sequence on shield loading behavior, two groups of five adjacent shields (shields 81 to 85 and 121 to 125) were monitored during panel 5 mining.

Gate Road Instrumentation

Pressure transducers were attached to hydraulic borehole pressure cells (BPC) installed in the roof, panels, and pillars of the gate roads around panel 1 at sites 1, 2, and 4. Site 3 was not connected to the monitoring network, and data were collected using chart recorders. Panel 2 monitoring included sites 1, 2, 3, 4, and two additional sites (5 and 6) in the panel 2 headgate. Entry convergence and roof-bed separation were monitored during portions of panel 2 mining. During panel 3 mining, monitoring was continued at sites 5 and 6. Instrumentations at sites 7, 8,

and 9 were installed to monitor a modified pillar arrangement (site 7) and possible bump zones (sites 8 and 9). These three sites were monitored during mining of panels 4 and 5. Figure 12 shows a detailed layout and cross section through site 4, which is a typical section for all pillar sites.

At sites 1 and 2, conventional mechanical chart recorders were installed along with the GCMS components to verify the data obtained from the monitoring system. Utilizing chart recorders was discontinued after a few months when it became evident that the GCMS 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. Therefore, significant effort was directed toward improving system components to provide reliable operation of the GCMS.

During panel 1 mining, shield-monitoring reliability was low, around 50% to 60%, primarily owing to cable damage on the longwall face and monorail area. Reliability was improved significantly for subsequent longwall face

Panel 2 →					← Abutment pillar →						← Yield pillar →				← Panel 1 →			
12	11	10	9		8	7	6	5	4		3	2	1		16	15	14	13
o	o	o	o		o	o	o	o	o		o	o	o		o	o	o	o

KEY
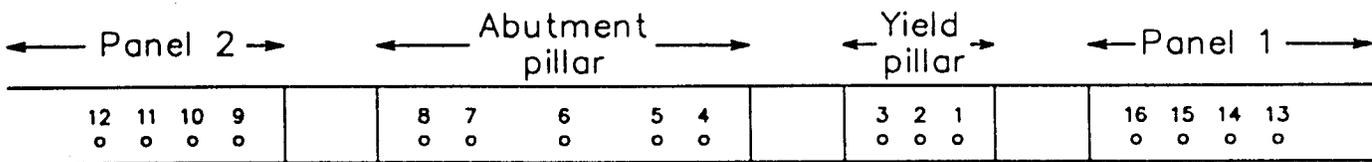
12
o BPC

Not to scale

Figure 12.—Cross section through gate road instrumentation site 4.

installations (panels 2-5) by 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, upgrading and eliminating wiring connectors, and applying waterproofing coatings to accessor cards.

GCMS interruptions that occurred subsequent to panel 1 mining included both planned and unplanned power outages and disruption of long-distance phone service between the mine site and DRC. The system can operate on battery power for about 4 h after the mine power is disconnected; however, data collection was occasionally interrupted during extended longwall power moves and

over idle weekend and holiday periods. Installation of the secondary computer at the mine surface eliminated data collection interruptions caused by disruption of long-distance phone service. The secondary computer also provided mine management with access to the real-time geotechnical data collected by the GCMS instrumentation network.

Overall reliability of the GCMS for panels 2-5 was approximately 85%, including downtime from both external sources (telephone and power) and internal sources (cables, components, and sensors). Data collection reliability of the BPC instrumentation sites, which are located away from 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. The previous sections have shown the capabilities of the GCMS for continuous monitoring of ground control data. This section discusses techniques developed for managing and analyzing the large quantities of information supplied by the monitoring network.

Processing and analysis operations are performed using a variety of commercial and custom software. Figure 13 illustrates the general sequence of data management and analysis within the GCMS. Basically, the data collected from the underground instrumentation network are combined with other pertinent information such as face position and geologic conditions, processed to reduce data file size, and analyzed using various techniques.

An advantage provided by the GCMS 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, data loggers, 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 input to the computer (or manually plotted) before analysis can begin. With the automated data collection system, large quantities of information are collected and processed automatically and continuously, and are available to mine personnel in near real time.

The GCMS was used to continuously monitor and analyze shield loading behavior and ground pressure distributions at the study mine. Management of the monitored data included processing and editing the raw data to
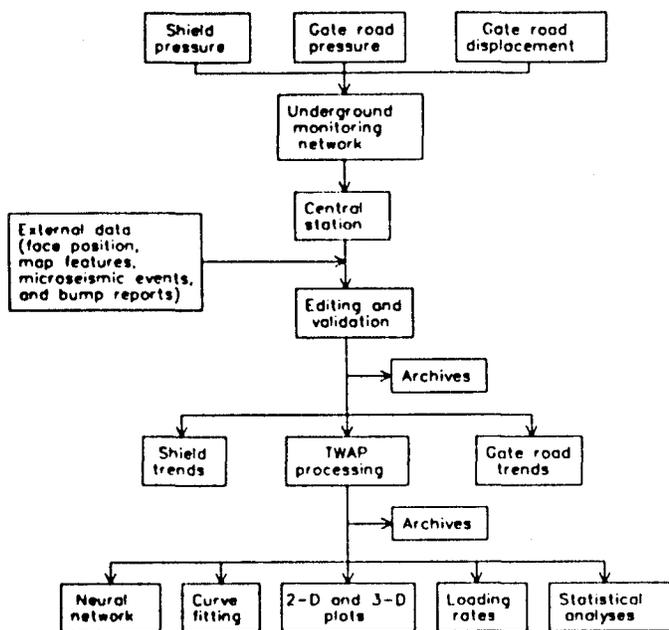
Figure 13.—GCMS data management flowchart. TWAP = time-weighted-average pressure.

reduce the amount of data that must be analyzed, validating the quality of the data through inspections of trend plots, converting the binary data to formats more suitable for analysis, and archiving the data for future use. In addition, external data were digitized to enable inclusion of geologic data, bump occurrence information (location, magnitude, time of occurrence, etc.), face positions, and microseismic data into the analyses. For example, shield pressure trends were analyzed and compared with plots of pillar pressure and gate road deformation behavior as a function of face position and time. Various analytical techniques were employed to evaluate current ground conditions and to anticipate conditions in advance of mining.

DATA MANAGEMENT SOFTWARE

The main control station 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. The data files contain a series of records consisting of instrument number, time, data value, and communication status. Communication status indicates whether communication between the sensor and the system has been interrupted. The Model 400 System creates a separate data file every hour. Because of the many pressure changes that occur during shield cycling activities, the data files require significant amounts of disk

space; data files for 1 day occupy approximately 2.5 Mb of disk space.

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 will have many small pressure changes owing to the shield operation characteristics and the electronics of the system. Minor fluctuations in the electrical signal alone produce numerous 1-bit pressure changes in the data files; with the 8-bit accessor cards used with the monitoring system, a 1-bit fluctuation equates to about 0.28 MPa (40 psi). These small fluctuations are edited out; only pressure changes greater than 1 bit are retained. Periods of communication interruption less than 1 min long are also eliminated from the data file storage. The resulting processed files occupy only about 10% of the original space while retaining the significant content of the raw data files. The file size is further reduced for storage using commercial compression utility software that permits maximized storage while leaving the data unaltered.

Most of the analysis programs require input data in the form of text files that list 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 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.
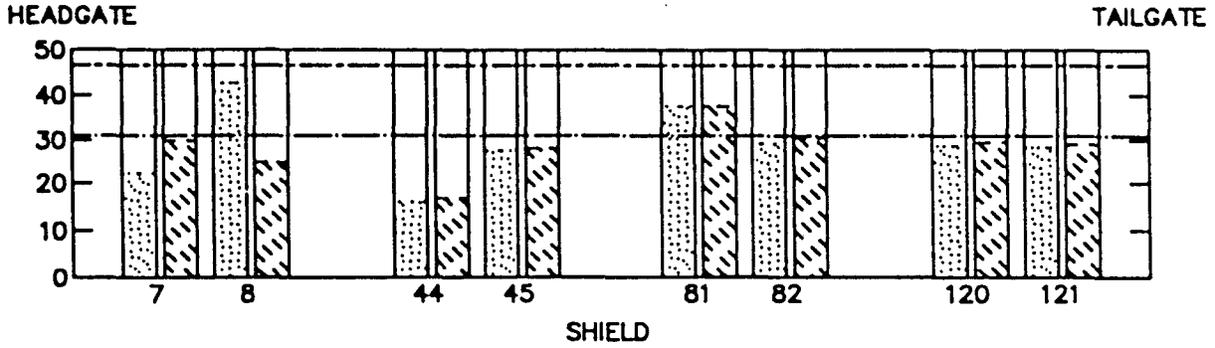
DATA DISPLAY CAPABILITIES

The GCMS 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 either in numeric form or as bar graphs and can be customized by the operator. The trend displays access historical data files stored on computer disk and permit examining trends from any prior monitoring period.

The capabilities of the GCMS 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 14, an actual display of shield data from panel 2, shows shield-leg pressures on all eight monitored shields in bar graph format (figure 14A) and as trends of the preceding 30-min interval (figure 14B). Examination of this shield data display provides information relative to shield-leg pressure magnitude and uniformity,
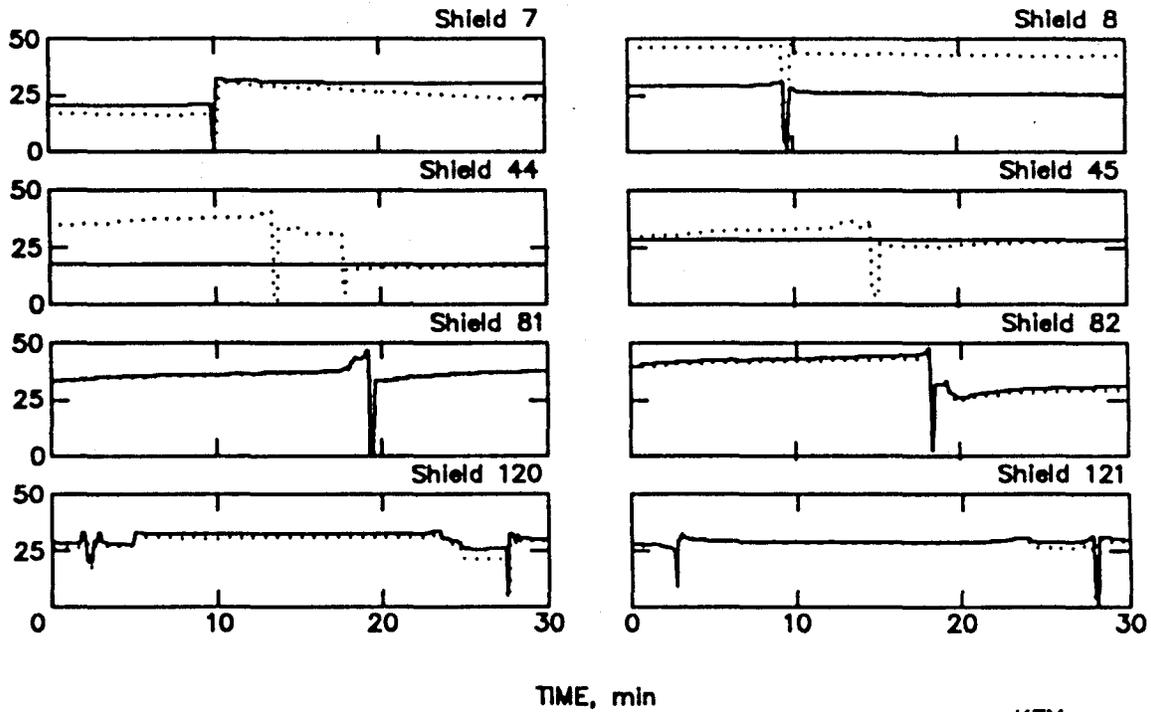
A

B

Figure 14.—Display of real-time shield data from panel 2. A, Bar graph display with shield-leg pressures; B, 30-min trend display.

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 in figure 14B 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 (1). For example, referring to the figure 14B shield 44 trend plot, the unchanging low 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). Also referring to figure 14B, the trend plot for shield 8 indicates uneven leg pressures, which may indicate either malfunctioning shield operation or malfunctioning monitoring-system components.

Data from the monitored instruments are automatically saved on computer disk to provide a permanent record. The historical data trend display program accesses the data files and permits examining data trends in more detail than the continuously updated trend displays. For example, typical shield loading variations during a production shift are shown in figure 15. 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 also used to evaluate the quality of the data by identifying abnormal values caused by malfunctioning instruments, sensors, accessors, or other equipment (shields). In addition, unusual loading conditions are also identified and examined in greater detail.

DATA ANALYSIS SOFTWARE

Data analysis has primarily been concerned with evaluating shield-leg pressure behavior using various parameters calculated from individual shield cycles. A shield cycle comprises the time interval from when the shield is reset after advancing until it is lowered prior to the next advance. Normal cycles, during production shifts, are approximately 30 min long; longer cycles occur during shift changes and over idle shifts. Generally, pressure continues to increase over the longer cycles, often approaching the yield setting of the shields.

Text files of the shield data, obtained from the GCMS 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. TWAP is the computed time-weighted-average pressure for each shield cycle. The software examines the pressures from the instrumented shield legs and eliminates erroneous data from malfunctioning sensors, accessors, or shield components. For an

example of erroneous data, the tailgate leg of shield 44 in figure 14B is not following the headgate leg in either pressure magnitude or cycling timing. The sensor or accessor on the shield 44 tailgate leg is apparently malfunctioning, even though a good communication signal is being transmitted to the main control station. The program also calculates a reliability percentage for each sensor.

Shield data analysis tasks have been handled primarily by a commercial spreadsheet program. Text files containing the processed TWAP information derived from the shield data 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 with 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 data are processed to remove the effects of long cycle times, low setting pressures, and other conditions associated with known shield operating procedures rather than changes in ground conditions.

Gate road pressure data are also imported into the spreadsheets and combined with face position information to evaluate pillar yielding and load transfer behavior. Several utility programs were developed to improve the efficiency of data importing, editing, and calculation steps. The spreadsheet data are exported as text files, for further processing, and as graphical displays, 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 have been effective in displaying the relationship between high shield pressures, local geological features, and zones of ground control problems. Figure 16 illustrates a three-dimensional plot of processed shield results for panels 2 and 3 along with the location of geologic slip zones.

EVALUATION OF GROUND CONDITIONS

The detection and management of ground control hazards associated with 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 not sufficient 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 (6).

Data from the GCMS are analyzed to evaluate rock mass behavior during longwall panel mining, with particular emphasis placed on comparing data patterns with
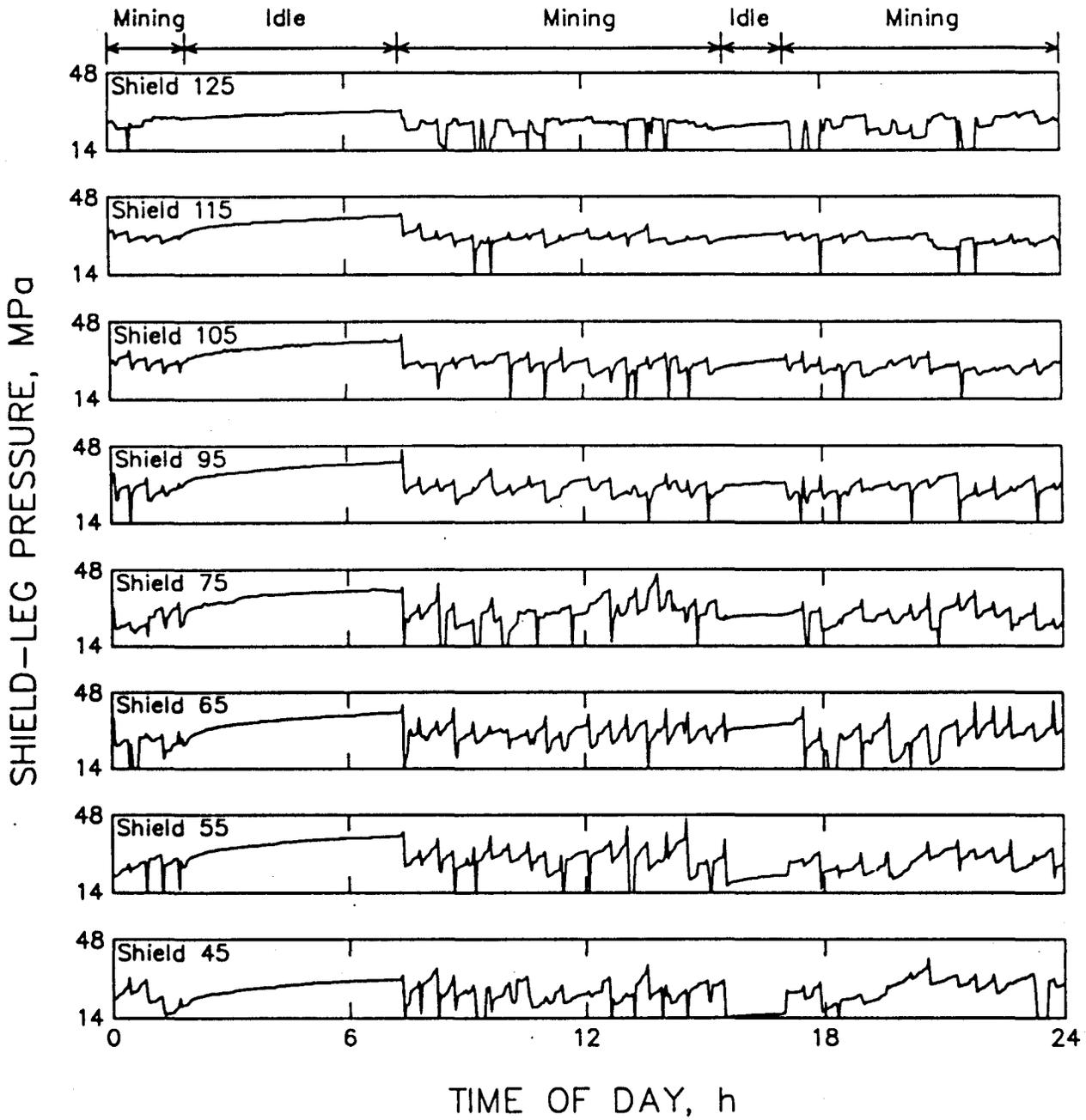
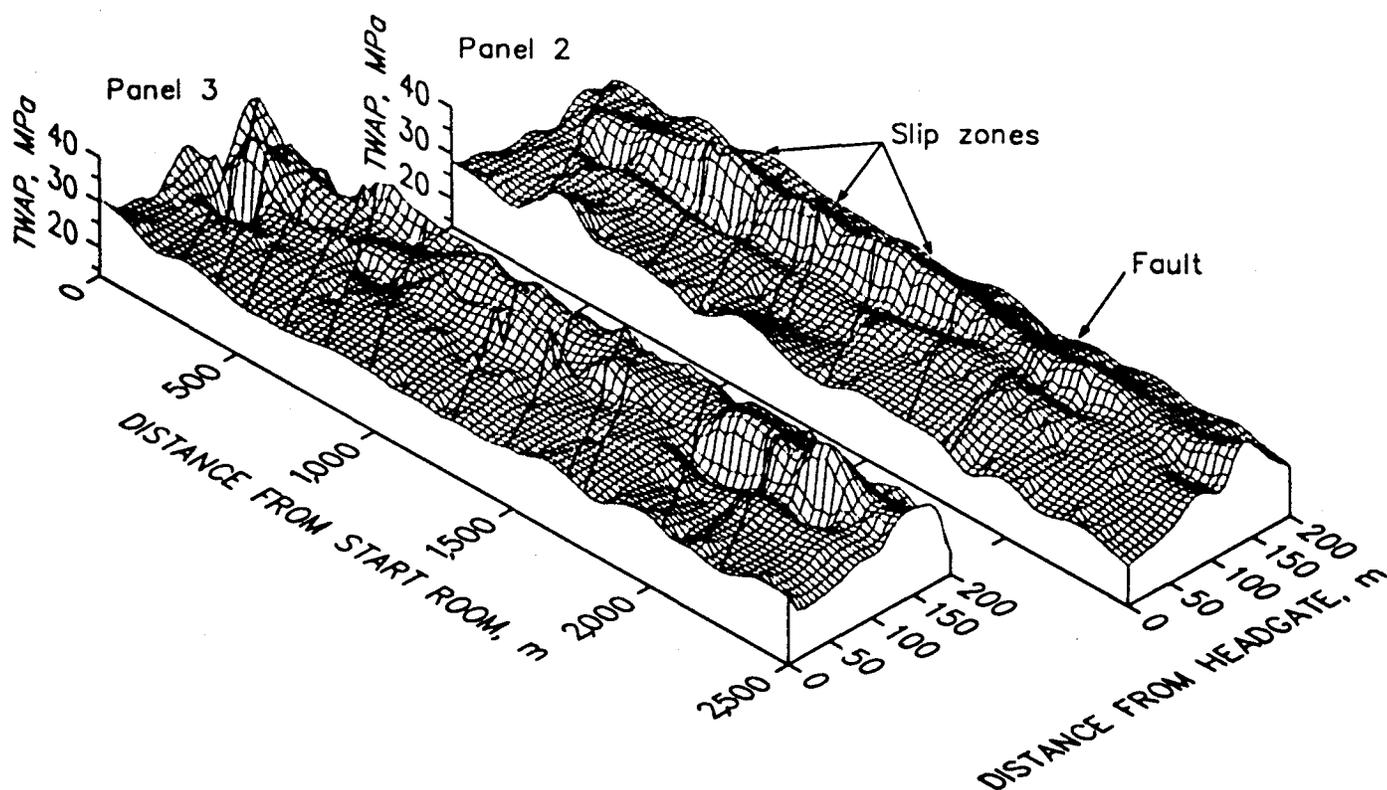Figure 15.—Shield load variations during a production shift.

Figure 16.—Comparison of panels 2 and 3 TWAP results with geologic slip zones.

observed ground conditions and local geologic settings. Ground conditions at various locations around the longwall panels were investigated through review of GCMS and site data, discussions with mine personnel, and in-mine observations. Concentrated efforts were directed toward analyzing certain tailgate areas of panels 2 and 3 where several floor heave and bump events occurred. A ground control hazard evaluation map was developed for these areas, as shown in figure 17 (7). The hazard map superimposes contour plots of the shield TWAP results for panels 2 and 3 with locations of geologic slip zones and an isopach of the immediate mine roof. This type of plot, automatically produced by the GCMS in near real time, provides the mine operator with information to evaluate anomalous pressure behavior associated with specific geostructural conditions and to initiate appropriate ground control procedures.

The following discussion provides additional examples of near real-time data collection, analysis, and results from the study mine to demonstrate the capabilities of the GCMS.

Gate Road Pillar Behavior

BPC data were readily examined using historical data trend plots. Figure 18 is a plot of site 4 yield pillar pressure cell readings over a period of 4 days as the panel 1 face was mined to a position approximately 122 m (400 ft) past the pillar site. The data plotted in the figure illustrate progressive pressure decrease (possible pillar yielding) of the pillar edges (cells 1 and 3) coincident with a pressure 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 load transfer and pressure data are transmitted continuously to the mine surface for rapid assessment by mine engineering and operations personnel.

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
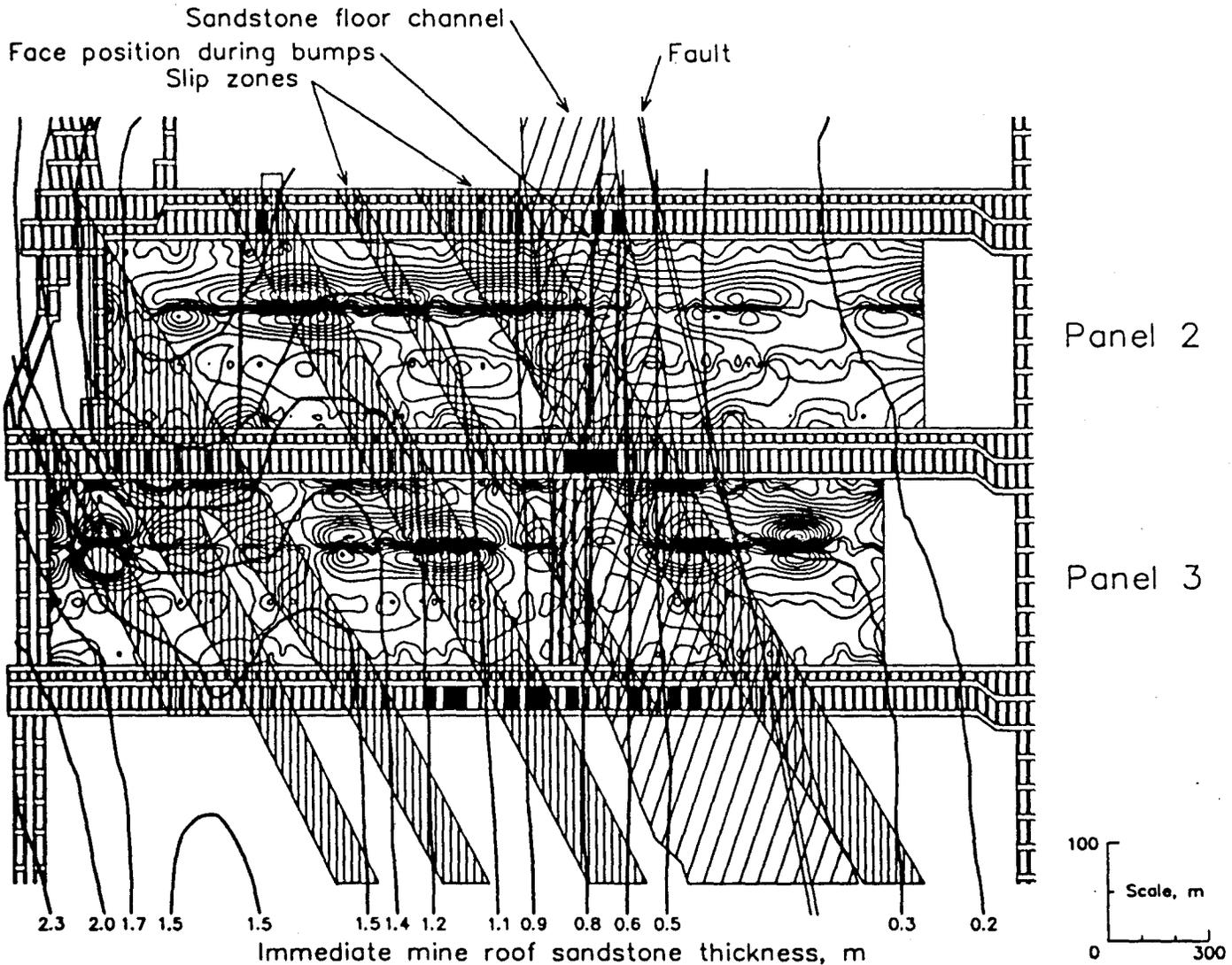
Figure 17.—Ground hazard evaluation map.

and face loading conditions (6). A significant phenomenon, detected through the shield-monitoring program, involves large, rapid shield pressure increases associated with tailgate bump occurrences and major roof caves in the gob. Anomalous pressure increases were first detected while monitoring the start of panel 2 mining (the initial cave of panel 2), where pressures on the four midpanel shields increased rapidly to yield pressure during two consecutive cycles. Figure 19 shows the detail of these cycles, which occurred when panel 2 had been mined approximately 61 m (200 ft) from the start room. As shown in figure 19, the first rapid pressure increases occurred in midcycle; 1.4 h later another large pressure increase occurred. According to the mine personnel working at the face, a major roof cave occurred as noted on figure 19, approximately 2 h after the second increase. The shield pressures did not decrease after the recorded cave, but remained at yield pressure until the shields were advanced at the start of the next production shift (6).

Rapid pressure increases were also observed on several occasions when tailgate bumps occurred immediately ahead of the face during mining of panels 2, 3, and 4.

A

←— Panel 2 —→   ←——— Stiff pillar ———→   Yield →   ←— Panel 1 —→
                                             pillar

4   3 2 1
O   O O O

KEY

4
O Cell location

B

PRESSURE, MPa

KEY
——— Cell 1
········· Cell 2
– – – Cell 3
—— — Cell 4

60

50

40

30

20

10

0   24   48   72   96

TIME, h
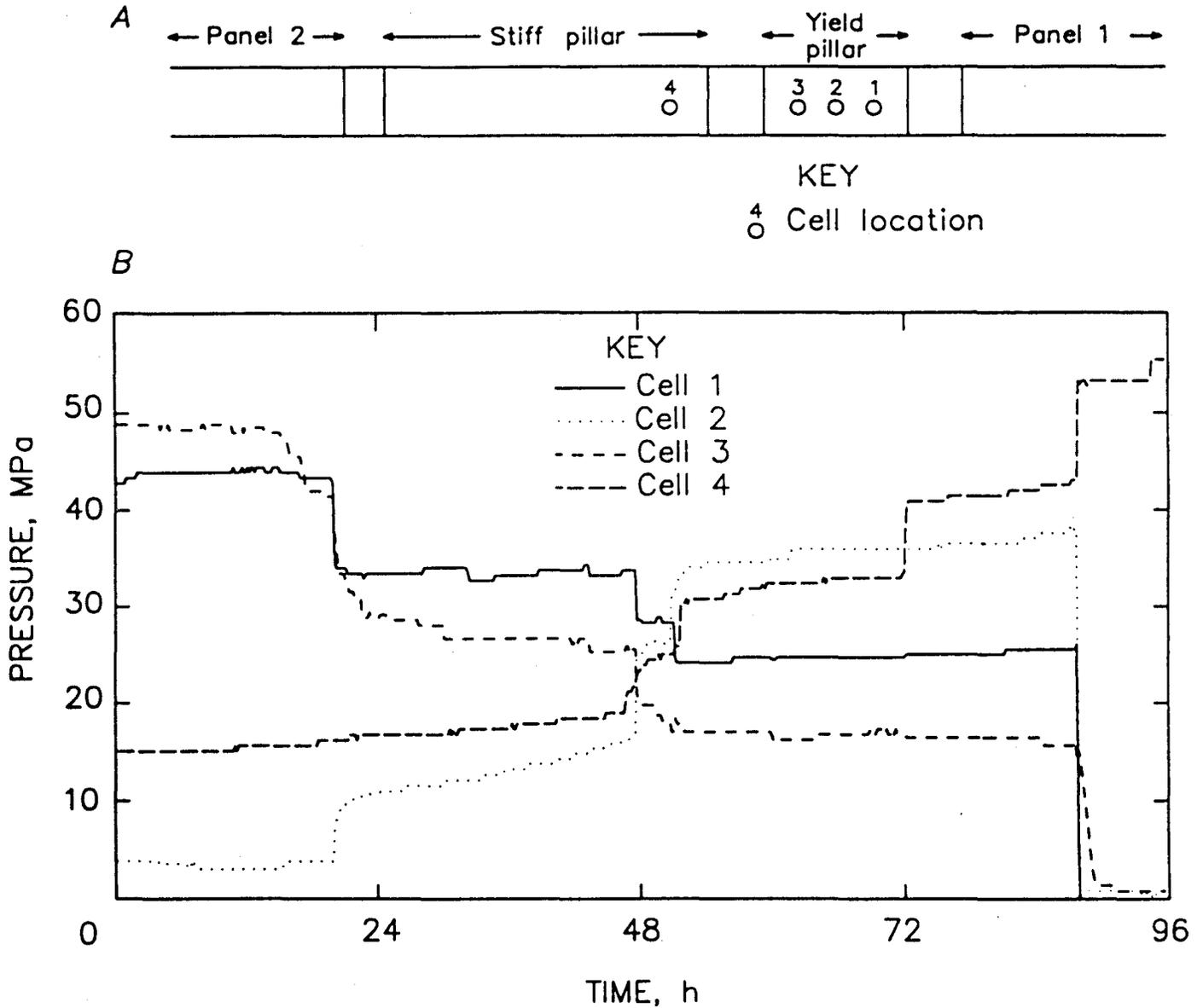
Figure 18.—Yield pillar pressure cell results. A, General instrumentation cross section showing cell location. Yield pillar width = 10.7 m (35 ft); stiff pillar width = 24 m (80 ft); B, BPC pressure results.

Figure 20, a plot of both shield and pillar pressures during a bump occurrence, 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

18

Figure 19.—Shield-leg pressure results during panel 2 first cave.

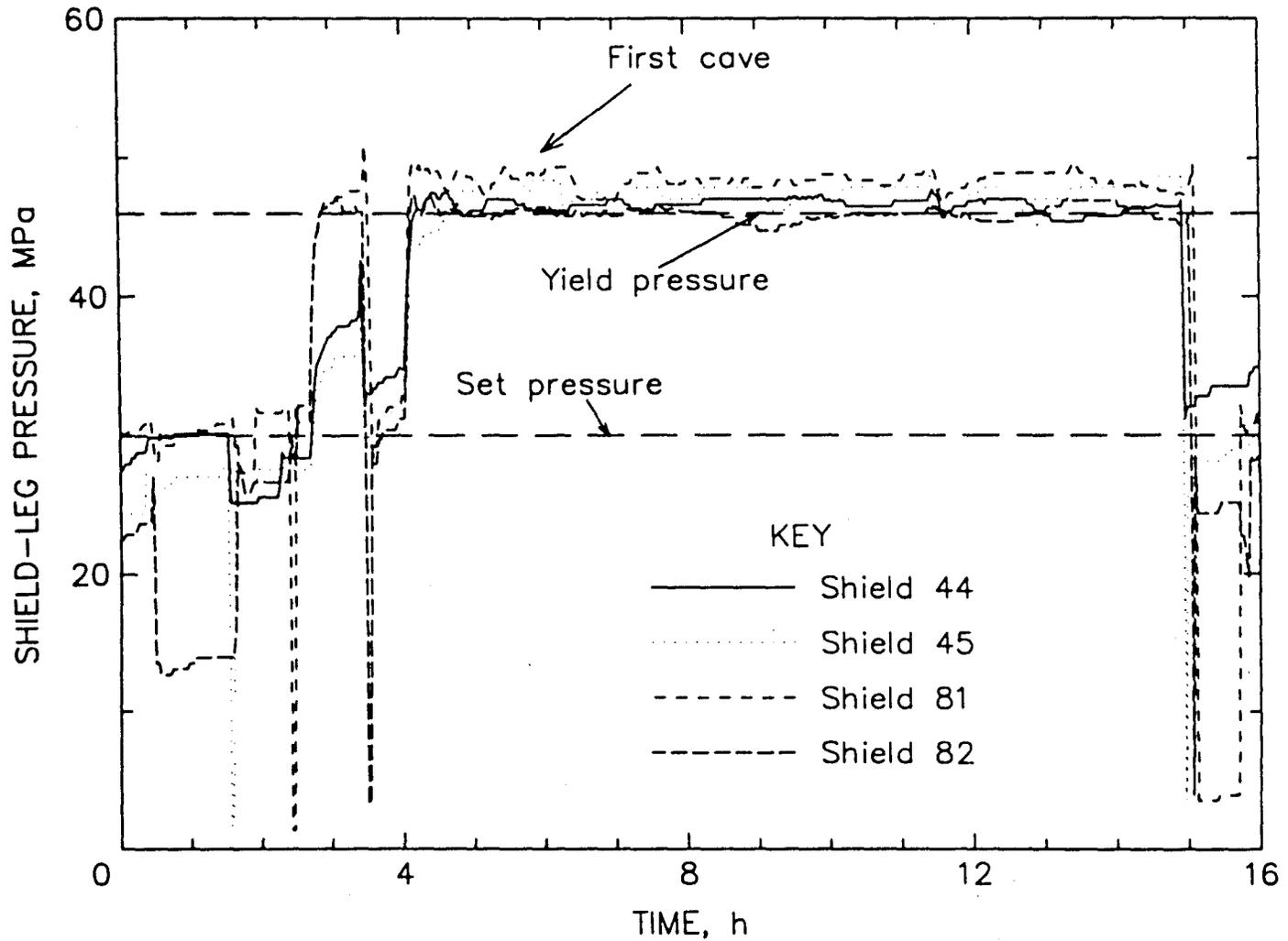approximately the same time as the rapid pressure increases in the shields and the stiff pillar. Shields 81 and 82 on the panel 2 face showed no corresponding pressure increase, suggesting that the influence of this tailgate event extended no more than about 61 m (200 ft) into the panel.

Additional tailgate bump events during mining of panels 2, 3, and 4 (locations shown in figure 10) 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 cycle 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 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 roof problems for a distance up to 45.7 m (150 ft) outby the face.
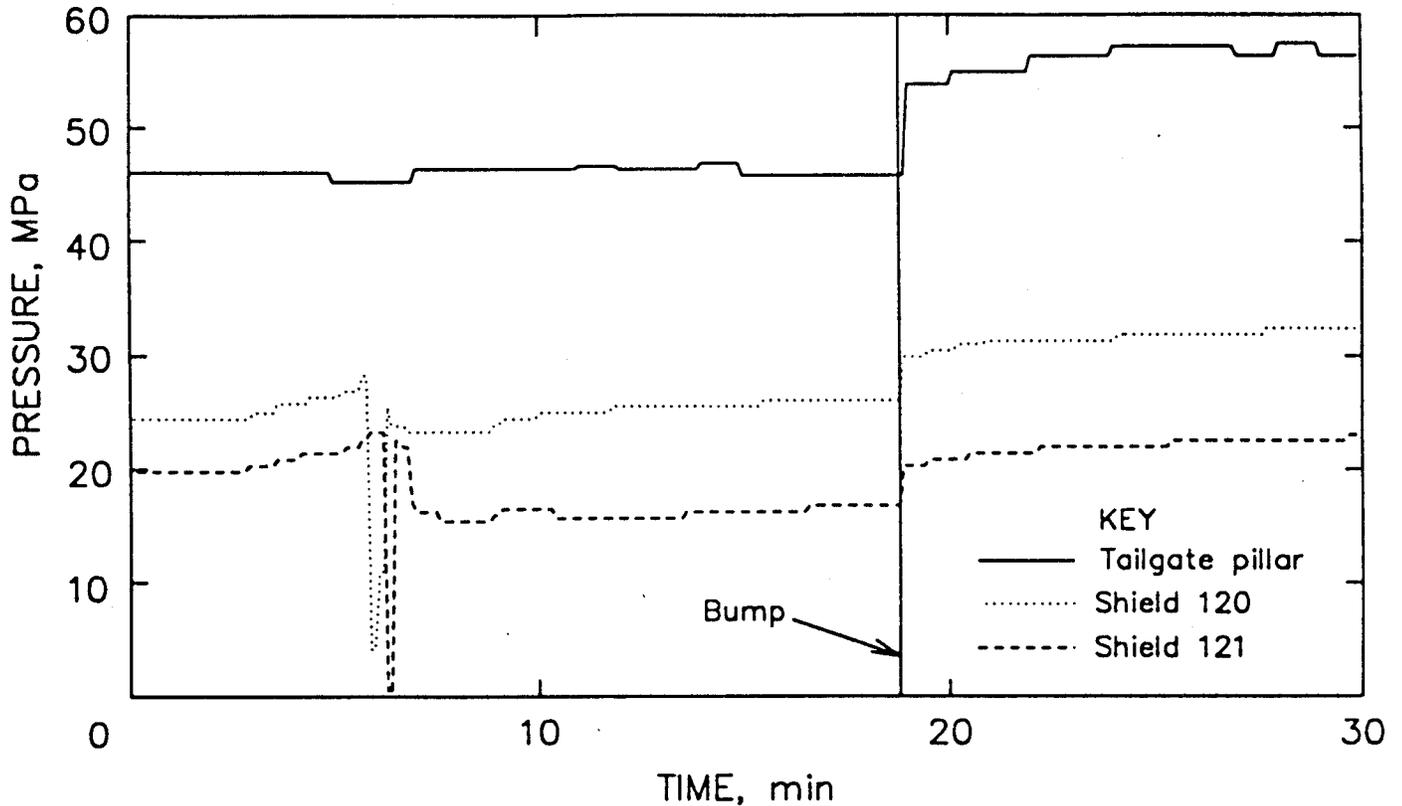
Figure 20.—Simultaneous shield and pillar pressure increases.

SUMMARY AND CONCLUSIONS

The development of the computer-assisted GCMS has greatly improved data quality, access time, and speed and accuracy of analysis over those of conventional monitoring methods. Continuous real-time acquisition of underground mine structure information, coupled with automated processing and evaluation of ground conditions, has proved valuable in accurately assessing mine structure behavior during longwall mining. The GCMS, which combines mine structural behavior data with other information, such as local geological conditions, has provided information on stress transfer and pressure buildup associated with several ground control events. Shield-leg pressure along with ground pressure monitoring results has 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 GCMS information, coupled with direct observations by mine personnel, permits a more complete real-time evaluation of face area hazardous conditions. Critical decisions related to coal mine ground control can be made with more information in a more timely manner.

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APPENDIX.—MONITORING SYSTEM SPECIFICATIONS

Owing to the proprietary protocols used by the mine-wide monitoring system, the majority of the equipment was obtained directly from the manufacturer, Conspec Controls, Inc. The phone cable, protective conduit, cable connectors, and remote computer were obtained from different sources, and most of the other computer equipment could also be obtained from other sources. Custom accessor enclosures were fabricated by the USBM, and the sensors were obtained from other sources. The following sections describe the general specifications, main features, and primary functions of each of the monitoring system components.

COMPUTERS

Four types of computers are used with the Model 400 System: primary, server, remote, and secondary. The common specifications for all computers are given below; differences are listed with the descriptions for each computer type.

80386 DX - 25 MHz	4 Mb RAM
1 hard disk drive	1 serial port
2 floppy disk drives	1 parallel port
VGA video display card	coprocessor not required
color VGA monitor	ISA bus
mouse	101-key keyboard
security key in parallel port	MS-DOS 3.3

In addition to the security key, the Conspec software is also password protected. MS-DOS versions 5.0 and 6.0 are thought to be compatible, but have not been completely tested. Conspec does not recommend using version 4.0.

Primary Computer

The primary computer contains an eight-channel serial board for communication with seven different trunks; one channel is reserved. An alarm card is installed to provide an audible alarm capability, and the system uses a bus mouse to free the standard serial port for communication to the server. The current primary computer uses an 80-Mb hard disk, although a smaller unit would be adequate. A dot-matrix printer is connected to the parallel port to provide a printed record of alarms and lists of programmed points. The printing function can be turned off for individual points and for the entire system.

The system uses the Conspec CSS software and requires a device driver for the serial card. Currently, each

trunk supports 127 points (addresses), although additional instruments can be supported using multiple-address accessors. Upgrades to the system should permit a larger number of points per trunk, up to a total of 15,000 points for the entire system. The system scan rate can be adjusted from 10 to 100 ms. The current system operates at 65 ms for compatibility with the modem configuration. An on-site system connected directly to trunk cables should be able to communicate at the 10-ms scan rate. The system is currently set for three retries before reporting a communication failure; however, this value can be modified for other conditions.

The display operates in color text mode and offers a variety of options for viewing and entering data. The data entry section consists of a database of all points to be monitored. Each database entry contains information for the point number, trunk number, address, engineering units conversion, alarm levels and labels, and a text description. This section also controls whether the point is added to the scan list or merely stored in the database for future use or reference. The monitored data can be viewed as a series of user-defined screens displaying the data in engineering units, as a bar graph reporting the communication status, as a digital display of each point's address and data in binary form, and as a quick-reference view of communication status for the entire trunk.

Server Computer

The server does not use a mouse or alarm card. The multichannel serial card is similar to the serial card in the primary computer and permits communication with eight remote computers. An additional serial card can be installed to add eight additional remote users. The server receives all changes of either data or communication status from the primary computer and saves the changes in binary form on the hard disk. Currently, a 200-Mb hard disk is installed, which becomes filled after approximately 3 months of monitoring. Also stored is a log of all remote-user activity.

The server uses the Conspec CLINK software and requires drivers for the serial card(s) and, using DOS 3.3, a driver to access the large hard disk. User-selectable video screens permit monitoring communication with the primary computer and all activity with the remote users. For the current system, the video monitor and keyboard are shared between the primary and server computers by means of a manual switch box.

Remote Computer

The remote computers require a three-button mouse and a serial connection to the server; therefore, either a bus mouse or a second serial port is required. A large hard disk is recommended to adequately manage transferred trend data files and the real-time monitoring image files. Currently a 300-Mb disk is installed; however, a 100- or 200-Mb disk should be sufficient. The current system is using DOS 6.0 with no apparent problems.

The remote systems use the Conspec TERMINAL software, which provides functions of real-time monitoring, generation and editing of graphics displays, communication with the server, and trending. The monitoring display uses the VGA 16-color 640- by 480-pixel resolution mode. Communication with the server is conducted at 38,400 bps over a direct connection. Modem connection at slower speeds is possible but may be impractical for real-time monitoring. Following are descriptions of the major features of the main software functions:

Real-time monitoring. Data can be displayed as text, bars, strip charts, and arbitrary colored areas. Colors of the display can change to reflect different alarm modes. Several displays can be loaded into memory to automatically cycle between the displays at a selected interval. The mouse can be used to easily switch between displays.

Communication. Remote users can send simple text messages and transfer data files to and from the server. DOS functions can also be executed, via a shell, without leaving the monitoring environment.

Graphics Editing. A reasonably complete editor is supplied, which permits creating various graphics primitives (lines, boxes, text, circles) and assigning dynamic links to specified areas. A pixel editor is also included for precise editing. Selected areas of the image, including links, can be saved on disk to permit multiple pasting of similar objects in a single display or between multiple displays.

Trending. The trending package provides for transferring data files from the server to the remote, editing templates, which describe the specific points to trend and how the data should be interpreted, plotting the trends using the templates, and saving trend plots for future reference.

Secondary Computer

The secondary computer is located at the mine surface and provides for continuous operation of the system in the event of a communication failure between the mine and the primary computer at DRC. Also, the secondary computer provides a backup copy of the data files and permits monitoring the system at the mine surface. The secondary system requires a multichannel serial board, an alarm card, and a three-button mouse. A 200-Mb hard disk is installed to handle the large amount of data, and a printer is connected to the parallel port. The computer is connected to the monitoring system through a dual-access area controller (DAC), which is connected in series between the long distance modem from DRC and the local modem connected to the underground components.

The Conspec CMS software is installed on the secondary computer to integrate the functions of the primary and server computers, and a remote computer. The software is managed using DOS 5.0, QEMM386 memory manager, and Desqview multitasking software to permit two or more programs to run simultaneously. The primary and server portions of the software run continuously to provide full-time monitoring of the data stream and communication status. The remote (graphics) portion of the software and other utility programs are only executed when required.

MONITORING NETWORK COMPONENTS

This section describes the components of the monitoring network between the surface computers and the underground sensors, including components for communication, power, and local control.

Modems

A pair of long-distance modems connects the primary computer to the mine surface and the secondary computer. A pair of local modems connects the mine surface station to the UCS located in the mine's main entries near the mouth of the active longwall panel.

Long-Distance Modems. Gandalf 419 stand-alone and RM3419 rack-mount modems provide a dual-channel capability with either one channel operating at low speed or two channels operating at high speed, resulting in an effective transmission rate of 4,800 bps per channel. Normally, the modems are operated in single-channel mode. However, during panel 5 mining, the modems were operated in dual-channel mode to enable independent communication between DRC and a microseismic system installed at the UCS. The long-distance connection required a line conditioner, installed by the telephone company, to improve the signal quality. This component was critical, especially when transmitting at 9,600 bps in dual-channel mode.

Local Modems. The normal installation uses Gandalf RM3120 rack-mount modems operating at 4,800 bps. The installation for panel 5 used a pair of Gandalf RM3419 modems to enable transfer of a second data channel underground.

Modem Interface Outstation. The modem interface is located at the mine surface station and combines a long-distance and local modem and adds a 25-pin output for the second channel of the long-distance modem. The 25-pin output generally follows the RS-232 standard; however, the signals are 12 V higher than the signals from a standard PC serial port. A pair of level-matching modems is used to connect the 25-pin output to a PC for data transfer. The DAC is connected between the two modems and draws power from the modem supply circuit. Isolator switches are installed on the phone cable leading underground.

Trunk Drivers

The trunk drivers convert RS-232 serial signals from the control computer to a proprietary signal used on the trunk lines and supply power for the trunk lines.

Local Trunk Driver. The local trunk driver provides a functional trunk line at the location of the primary computer and is used in the laboratory for testing purposes. The trunk driver incorporates a manual disconnect switch for installations where the trunk cable leads directly underground.

Long-Distance Accessor Outstation (LDA). The LDA combines a trunk driver with the underground side of the local modem pair. The trunk driver card provides an accessor checker interface for remote monitoring of individual accessor status. The LDA outstation also functions as the main power disconnect for the underground trunks.

Area Controllers

The area controllers function as independent controllers of all network components inby the controller. In addition, they provide the capability of translating addresses, enabling the physical card addresses to be different from the logical addresses programmed in the primary and secondary computers.

Intelligent Area Controller Outstation (IAC). The IAC is located at the underground control station and provides for independent control of the underground trunks if the phone connection to the primary or secondary computer is interrupted.

Dual-Access Area Controller Outstation (DAC). The DAC is located at the mine surface station and provides an interface between the system and the secondary computer. The DAC monitors the communication signal and assumes control of the system if communication to the primary computer is interrupted.

Accessor Trunk Extender Outstations (ATE's)

ATE's are optional and are installed on long or heavily loaded trunk lines to refresh the power and recondition the signal. A dual version (DATE) is available that supplies power for two trunks. Installation of an ATE is recommended when the length of a trunk line exceeds 2,400 m (8,000 ft). The ATE also provides an accessor checker interface.

Barriers

Barriers are installed on all trunks entering areas that require permissible equipment. The barrier limits the trunk power to 15 V and 150 mA. The cable shield and ground are tied together at the barrier. If power is interrupted to the barrier, the barrier trips. The barrier must be reset manually when tripped.

Enclosures

Several type of enclosures were used during the monitoring project. For most applications the enclosures performed satisfactorily; however, the extremely wet conditions along the face resulted in rapid deterioration of the accessors, which required frequent replacement. On the face, the enclosures were mounted on a shield leg or to the lemniscate assembly. At the gate road sites, the enclosures were mounted on timber frames or on cribs, or were hung from wire mesh installed on the roof.

Face Enclosures. Custom aluminum enclosures were fabricated to hold two accessor cards and two T-Hydronics pressure transducers. The enclosures were fitted with quick-connect bulkhead electrical connectors and tapered compression hydraulic fittings. Flanges were provided for mounting the enclosure on a lemniscate leg. All internal electrical connections were soldered, and the enclosure was sealed with a silicone gasket seal.

Gate Road Enclosures. For the gate road sites, the standard Conspec metal enclosures with door gaskets and cable grips were used. Spring connectors were used to connect the trunk and accessor wires. The accessor cards were mounted in the enclosure using plastic spring clips.

Junction Boxes

The junction boxes were also obtained from Conspec and were similar to the gate road enclosures, but without accessor clips, and constructed of a fiber-composition material.

Cables

Trunk cable was obtained in 300-m (1,000-ft) and 600-m (2,000-ft) spools and spliced using crimp connectors or with junction boxes. The initial phone cable installation used 300-m (1,000-ft) lengths of cable; the second installation used a single 1,500-m (5,000-ft) length. Cables were hung using plastic-coated hooks from the roof along one side of the entry or from the chains supporting the conveyors. Installation of cables in the main travelways was avoided to minimize interference from vehicular traffic.

Trunk Cable. The MSHA-approved trunk cable consists of four conductors and a shield. The power and ground wires are 12 ga, and the signal and shield wires are 18 ga. A standard-duty cable was used in conduit along the face; the remaining installations used a heavy-duty cable having an extra plastic jacket and a braided metal sheathing.

Phone Cable. The phone cable from the surface installation to the underground LDA consisted of four 18-ga conductors (two twisted pair). The cable used during the initial installation included a shield wire. A second installation used cable having an integrated support cable.

Conduit. Initially, heavy-duty trunk cable was encased in reinforced hose for protection from pinching between adjacent shields during shield moves. Connections were made to standard enclosures mounted on the instrumented shields. Once the custom enclosures were fabricated, standard-duty cable was installed in sectional lengths of 19-mm (3/4-in) diam plastic conduit and fitted with quick-connect connectors. The hose and conduit were routed alongside and fastened to the shield hydraulic hoses and shield framework with plastic cable ties.

Cable Connectors. Spring connectors were installed in the enclosures and junction boxes and soldered to the accessor cards for the transducer connections. Five-pin solderless connectors were installed on the 75-m (250-ft) trunk cable sections strung along the beltline. Five-pin prewired connectors with compression fittings were used in conjunction with the plastic conduit installed along the face. The connector wires were soldered to standard trunk cable threaded through the conduit.

Accessors

The pressure transducers were connected to Conspec A90 accessors, which accommodate the 0.5- to 5.5-V transducer output. A55 accessors, modified with a 5-V regulator, were used with the convergence meters. A56 4- to 20-mA accessors were used with the linear motion transducers, and A51 and A55 accessors were used with the sonic meters. To improve the reliability of the wiring connections, spring connectors were soldered to the accessor boards, replacing the standard slip-on connectors. The trunk connecting wires were also soldered directly to the boards to eliminate the slip-on connectors. The modified boards were coated with a waterproofing material to reduce corrosion.

SENSORS

A wide selection of sensors are potentially compatible with the monitoring system owing to the variety of accessors available. However, the selection is narrowed by the special requirements for underground use, particularly in areas requiring permissible equipment. The pressure and convergence transducers were used extensively, since they were classified permissible and could be installed in the main areas of interest (face and tailgate). The linear motion and ultrasonic sensors performed satisfactorily, but were only evaluated for a short time in the fresh-air areas of the headgate.

Pressure Transducers

Transducer: T-Hydronics model THV-LCV
Range: 0 to 70 MPa (0 to 10,000 psi)
Accuracy: ± 0.5%
Excitation: 10 to 35 V
Output: 0.5 to 5.5 V
Current: 2 mA
Accessor: A90

Linear Motion Transducers

Transducer: Raychco model PT 420-2
Range: 0 to 5 cm (0 to 2 in)
Resolution: infinite
Accuracy: ± 0.25%
Excitation: 14 to 40 V
Output: 4 to 20 mA
Accessor: A56

Convergence Transducers

Transducer: Serata closure probe
Range: 0 to 15 cm (0 to 6 in)
Resolution: 0.025 mm (0.001 in)
Excitation: 5 V
Output: 0 to 5 V
Current: 200 mA
Accessor: A55 with 5-V voltage regulator installed

Ultrasonic Distance Transducers

Transducer: Lundahl model DCU-7
Range: 0.6 to 3.0 m (2 to 10 ft)
Resolution: 0.76 mm (0.0025 ft)
Accuracy: ± 0.2%
Excitation: 5 V
Output: 0 to 5 V
Current: 35 mA
Accessor: A51 or A55