INTEGRATED SHIELD AND PILLAR MONITORING TECHNIQUES FOR DETECTING CATASTROPHIC FAILURES

By Robert M. Cox,[1] David P. Conover,[1] and John P. McDonnell[1]

ABSTRACT

The Ground Control Management System (GCMS) developed by the U. S. Bureau of Mines has allowed researchers and mine management personnel to monitor geostructural data remotely and evaluate ground stability conditions in real-time during high-speed mechanized extraction of coal from longwall panels. Because of the high rate of advance of mechanized longwall faces and the frequent encounter of changes in geologic structure, mine operators are finding it increasingly difficult to cope with the rapid changing ground conditions encountered during succeeding production shifts. The GCMS offers a solution to these problems by combining existing mine monitoring technology with automated computer analyses specifically formulated for ground control management.

The GCMS has been used to collect and analyze data from several longwall panels instrumented to evaluate (1) shield loading behavior, (2) ground pressure redistribution, and (3) ground failure modes associated with catastrophic floor bumps in tailgate roadways. This paper summarizes practical applications of the GCMS and shows how the system can be used to anticipate and detect ground hazards while mining progresses. Shield loading anomalies and ground pressure changes related to major panel roof failures and catastrophic tailgate roadway closures caused by floor bumps are discussed.

INTRODUCTION

The number of mechanized longwall mining systems installed and operating in U. S. coal mines during the past decade are shown in table 1 (*1*).[2] Also included in table 1 are the annual number of fatal and nonfatal accidents associated with the operation of longwall mining systems and reported by the Mine Safety and Health Administration (MSHA) for the period 1983 through 1993. Figure 1 shows the severity rate of accidents per year associated with longwall coal mining in the United States. The significant coal mine safety hazards associated with the use of high-speed mechanized longwall mining systems are shown in figure 2, and the relative number of accidents per year are shown in figure 3. During the past decade two coal mine disasters have occurred in longwall coal mines: the Wilberg Mine fire (1984), which resulted in 29 fatalities, and the Pyro explosion (1989), which caused 12 fatalities.

The most serious safety problems that frequently occur during the operation of a mechanized longwall panel are those specifically associated with maintenance of the tailgate roadways for adequate face ventilation and as alternative escapeways. Unexpected closures of tailgate roadways because of catastrophic ground failures, defined for the purpose of this paper as roof falls, floor heaves, and pillar bursts, are a constant operating problem for longwall mines and pose continuing dangers to the work force. It is not uncommon to have as many as 5 pct of the longwall faces in the United States idled on a given day because of premature gate road closures. These idle periods typically last about one-half shift, during which time remedial (supplemental) ground supports must be set in the tailgate roadway, under less than ideal working conditions, before

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

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

Figure 1
Severity Rate of Longwall Mining Accidents.

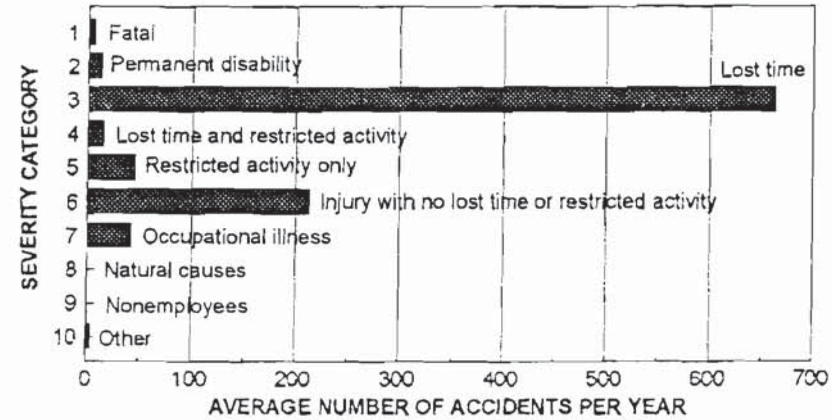


Figure 2
Significant Safety Hazards Associated With Mechanized Longwall Mining.

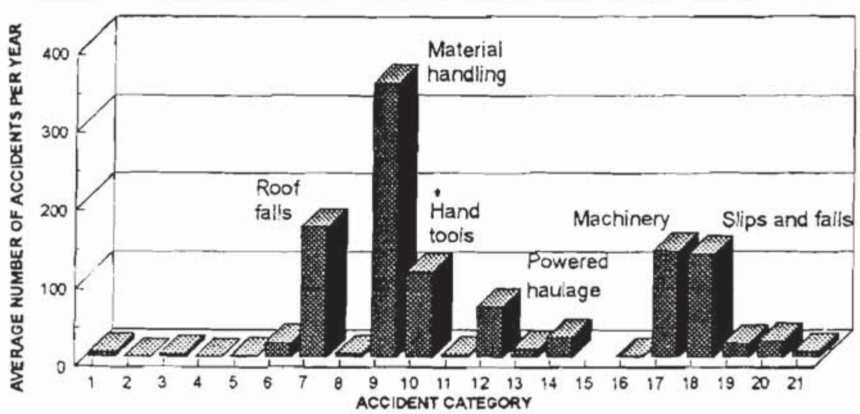
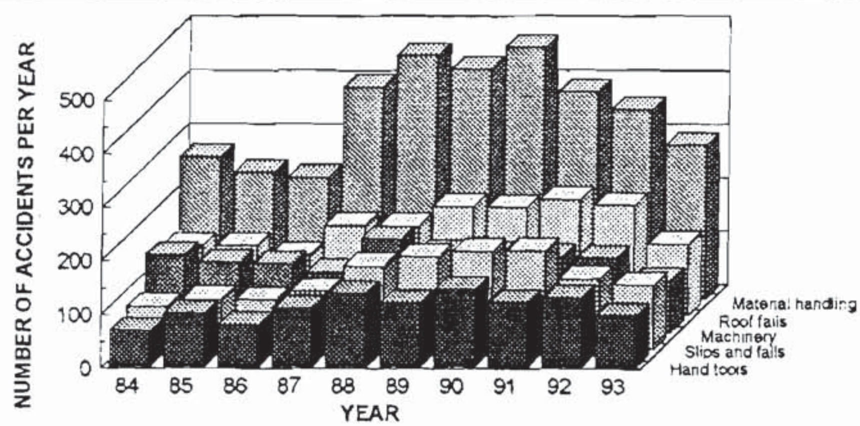


Figure 3
Rate of Significant Longwall Accidents.



coal extraction can resume in safety. These dangers are significantly increased for longwall faces operating in bump-prone ground. Some longwall faces have been known to be idled for several days or weeks because of catastrophic tailgate closures.

Table 1.—Summary of longwall mines and accidents by year.

Year	Operating longwall mines	Fatal accidents	Nonfatal accidents
1983	118	1	535
1984	112	[1]29	743
1985	108	1	759
1986	99	5	734
1987	96	2	1,047
1988	92	3	1,206
1989	95	[2]12	1,207
1990	96	5	1,239
1991	92	1	1,184
1992	89	1	1,087
1993	89	0	807

[1]Wilberg Mine fire.
[2]Pyro explosion.

The most significant problem facing coal mine operators using modern mechanized longwall mining systems is the difficulty of detecting and responding to changing ground conditions encountered by a rapidly advancing longwall face. Although computer systems have been used extensively to evaluate rock mechanics data (*2*), only recent advances in sênsor technology and computer monitoring systems have allowed improved techniques to be incorporated for the remote monitoring and evaluation of geotechnical data from underground coal mines (*3*). Computer-controlled mine-wide monitoring systems are improving safety and productivity in U. S. coal mines (*4*), and such systems have become commonplace for monitoring such diverse items as environmental conditions, electric power distribution, and equipment performance. Ongoing developments are providing additional capability and flexibility, such as control and operation of mining machines and haulage systems (*5-7*).

Although previous ground control studies (*6, 8*) have used data acquisition systems to collect information, the application of these systems in real-time analyses of geotechnical data for ground control planning has not been widespread. Real-time acquisition of data, coupled with automated computer processing, can provide important decision-making tools for mine management (*6, 9*). The current trend in monitoring system development is to integrate separate monitoring systems under the control of a central computer (*5-7, 10*). New computerized ground control technology must be compatible with existing monitoring systems to be of maximum benefit to the mining industry.

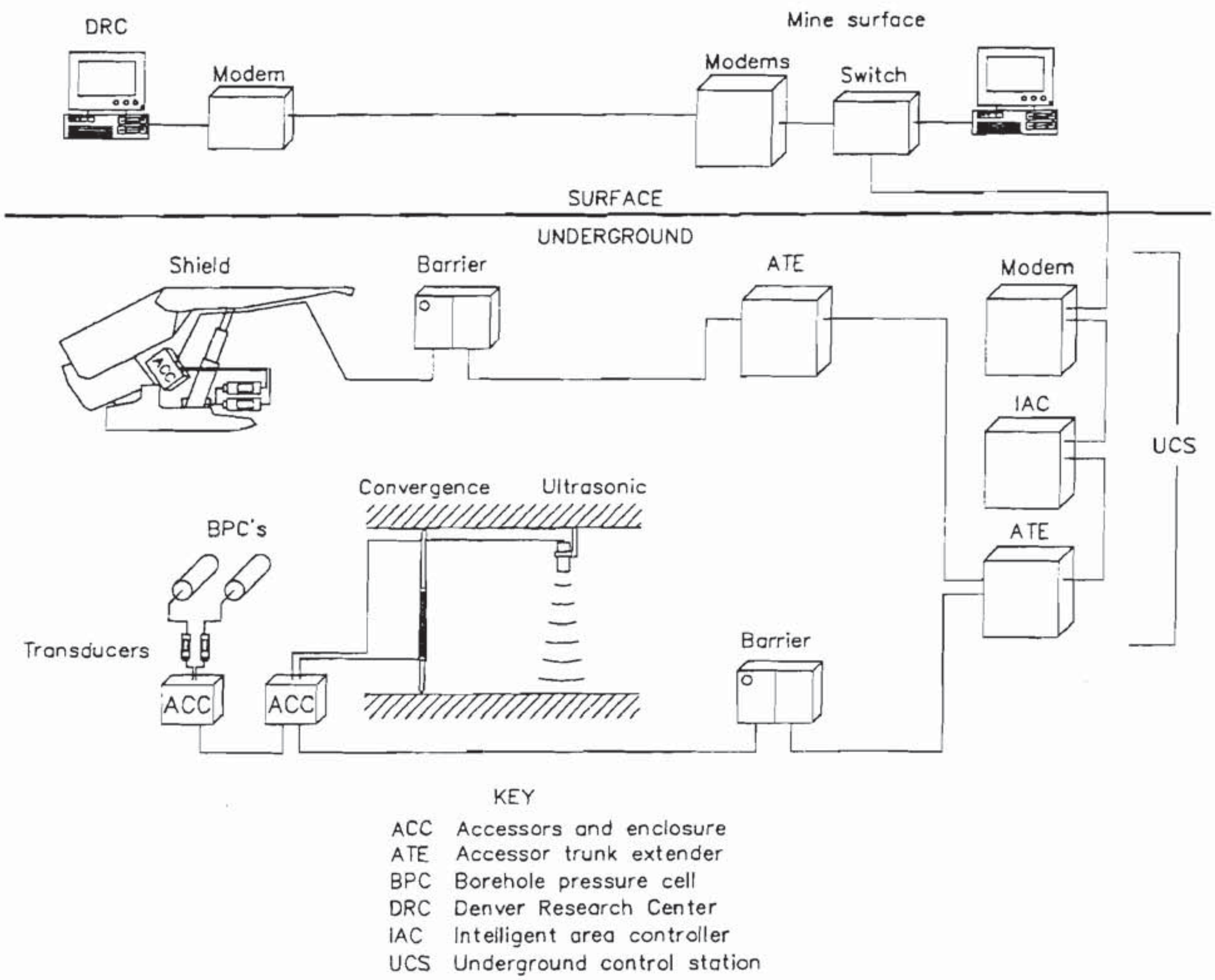
The automated Ground Control Management System (GCMS) developed by the U. S. Bureau of Mines (USBM) uses computerized mine monitoring and electronic sensor technology for the continuous acquisition and analysis of geostructural data (*10- 12*). The mine operator now has available a real-time ground control information tool for the effective management of ground stability on high-speed mechanized longwall panels. The computerized GCMS is designed to monitor ground response to the high-speed extraction of longwall panels continuously and to display geotechnical data, such as shield loads and ground pressures, in real time. The GCMS also processes and stores the data and can be used to create graphic displays for both real-time examination of ground stability conditions and to analyze historical trends in the geomechanics data for future mine layouts.

The GCMS is currently being used to monitor geostructural data and evaluate ground stability conditions during the high-speed extraction of coal from mechanized longwall panels in an underground coal mine in northwestern Colorado. To date, the capabilities of the GCMS have been demonstrated during the continuous monitoring and evaluation of data during the extraction of five consecutive longwall panels at the test mine. The resulting data have improved understanding of shield-loading behavior during face operations and ground failure modes associated with catastrophic tailgate roadway failures. A review of characteristic shield pressure patterns and the occurrence of shield pressure anomalies associated with ground failures are presented in this paper.

MONITORING SCHEME

A schematic of the GCMS instrument network is shown in figure 4. The entire system is comprised of commercially available equipment, and all underground components are MSHA approved for permissible use in underground coal mines. The existing system has been configured to monitor continuously shield-loading behavior across the longwall face and ground pressure changes associated with various gate road pillar systems. From time to time, various other sensors have been connected to the system to monitor strata movements. The actual numbers and locations of sensors and trunk cables can be adjusted as necessary to support a wide variety of monitoring programs. The system has also served as a test facility for evaluating the effectiveness of various prototype sensors being developed to measure ground control parameters.

Figure 4
Schematic of GCMS Instrument Network.

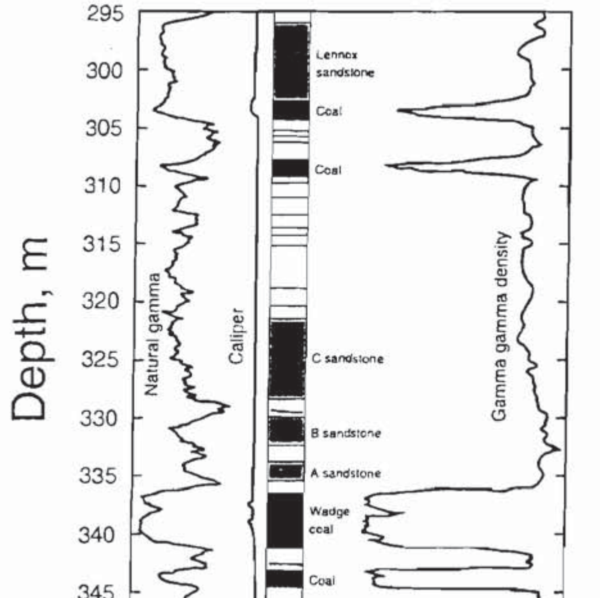


The test site mine is located in the Yampa Coalfield in north west Colorado, about 20 km (12 miles) west of Oak Creek, CO. The coal seam within the test area of the mine is about 340 m (1,100 ft) deep, has a uniform geologic structure, and an average thickness of 3 m (10 ft) (figure 5). The floor consists of interbedded mudstones and bony coal underlain by stronger sandstones and a lower rider coal seam. The immediate roof extends about 31 m (100 ft) above the coal and consists of four distinct layers (A, B, C, and D) of interbedded sandstones and shales overlain by two small rider coal seams occurring beneath a prominent sandstone unit (the Lennox). The remaining overburden consists of several hundred meters of shale beds capped by the massive Twentymile Sandstone.

The mine was developed using a three-entry gate road system with panels approximately 200 m (640 ft) wide and 3,000 m (10,000 ft) long. Panels are mined from west to east. Roadways are 6 m (18 ft) wide, small pillars are 9 m (30 ft) wide by 21 m (80 ft) long, and large pillars are 21 m (80 ft) square. Figure 6 is a map of the mine layout indicating the geometry of the longwall panels, pertinent geologic features, and the locations of gate road instrument sites.

Figure 5

Geophysical Log and Stratigraphy of Test Mine Site.



A double ranging drum shearer is being used to mine coal from the longwall face in 76-cm (30-in) cuts using a modified half-face cutting method. In the first pass (from headgate to tailgate), the center of the coal face is cut about 40 cm (16 in) deep, and on the return pass (from tailgate to headgate), the full seam is cut 76 cm (30 in) deep. About 15 cm (6 in) of top coal is left for product quality control. Experience at the mine has shown that this method of mining has improved longwall face roof control and miner safety by reducing stress concentrations along the face and minimizing the hazard of serious face spalling. The method also provides even loading of the face conveyor and section belts.

The longwall face roof is supported by 560-mt (620-st), state-of-the-art, two-legged, electrohydraulic lemniscate shields. The average rate of advance of the high-speed mechanized longwall panels is shown in figure 7 and has increased from 9.4 m/d (30 ft/d) for the first panel to approximately 12 m/d (40 ft/d) for panels 4 and 5. The average panel rate of mining has been about 300 m (1,000 ft) per calendar month, with the mine typically working eight 10-h shifts per week.

The computerized GCMS instrumentation plan was designed to monitor ground behavior continuously during the mining of successive longwall panels. To date, a total of nine gate road ground pressure sites have been instrumented and monitored during the mining of the five longwall panels shown in figure 6. The layout of a typical gate road instrument site is shown in figure 8. Each site consists of borehole pressure cells (BPC's) installed at various depths within boreholes drilled into the coal pillars and panel ribs. These sites are designed to monitor abutment loading characteristics of the coal pillars and panel ribs as adjacent longwall panels are mined.

Although gate road ground pressure instrument sites provide valuable ground control information, they are very labor intensive to install, expensive, and of limited utility for continuous panel-wide monitoring of geostructural conditions. Shield leg pressure monitoring, on the other hand, requires only a single installation per panel and provides continuous data during the extraction of the complete panel. Thus the real-time monitoring of shield-loading behavior is ideally suited for the continuous dynamic analysis of ground stability in and around an active longwall face (*11*).

The locations of instrumented shields across the longwall face were varied for successive panels, as shown in figure 9, to study typical shield-loading behavior along the face and relative behavior between adjacent shields, and to monitor roof-loading characteristics near the tailgate roadway. For practical purposes, such as the close working space along the face and the power limits imposed by the permissible power barriers, no more than 10 shields could be instrumented with one trunk cable (i.e., 20 sensors, 2 legs per shield).

The automated GCMS permits the continuous viewing of the status of all the geotechnical instruments in real time, either in numerical text or graphic form. For example, figure 10 shows a real-time computer display of the positions and current pressure readings of each of the shield pressure transducers located along the panel 4 face and the BPC's at gate road pillar sites 7, 8, and 9 located between panels 4 and 5, as indicated in figure 6.

Figure 6
Test Mine Layout, Geotechnical Features, and Instrument Sites.

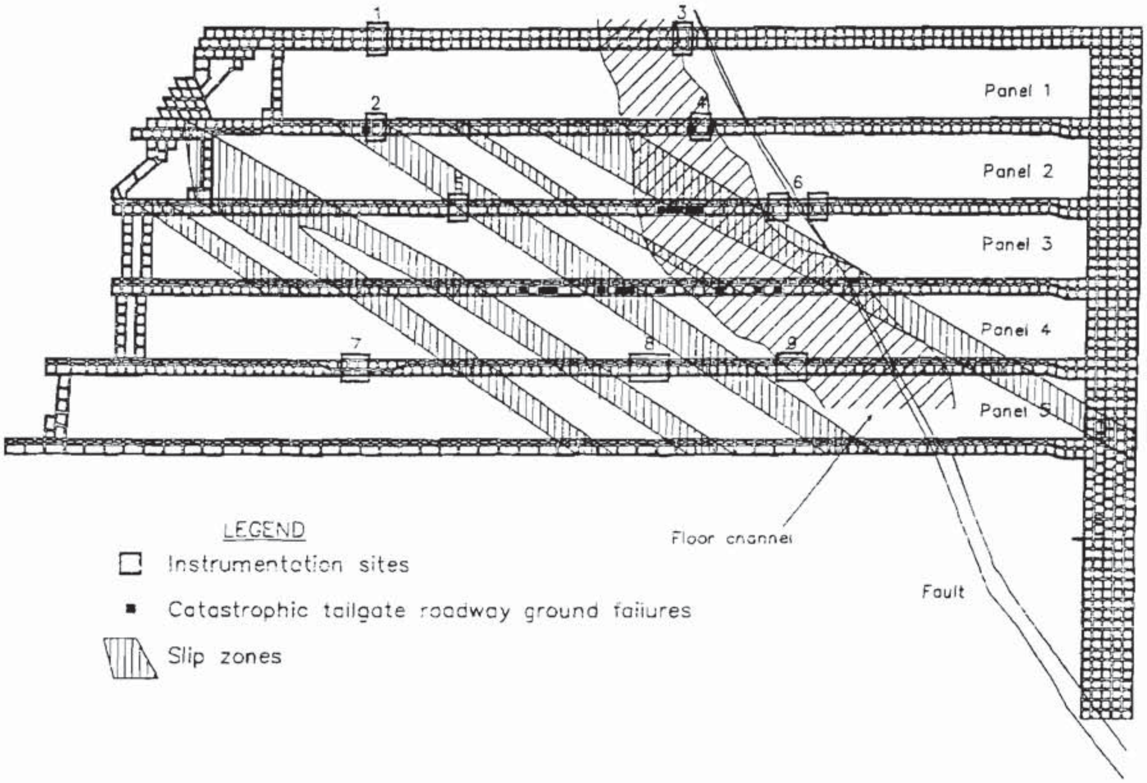


Figure 7
Rate of Advance of High-Speed Mechanized Longwall Panels.

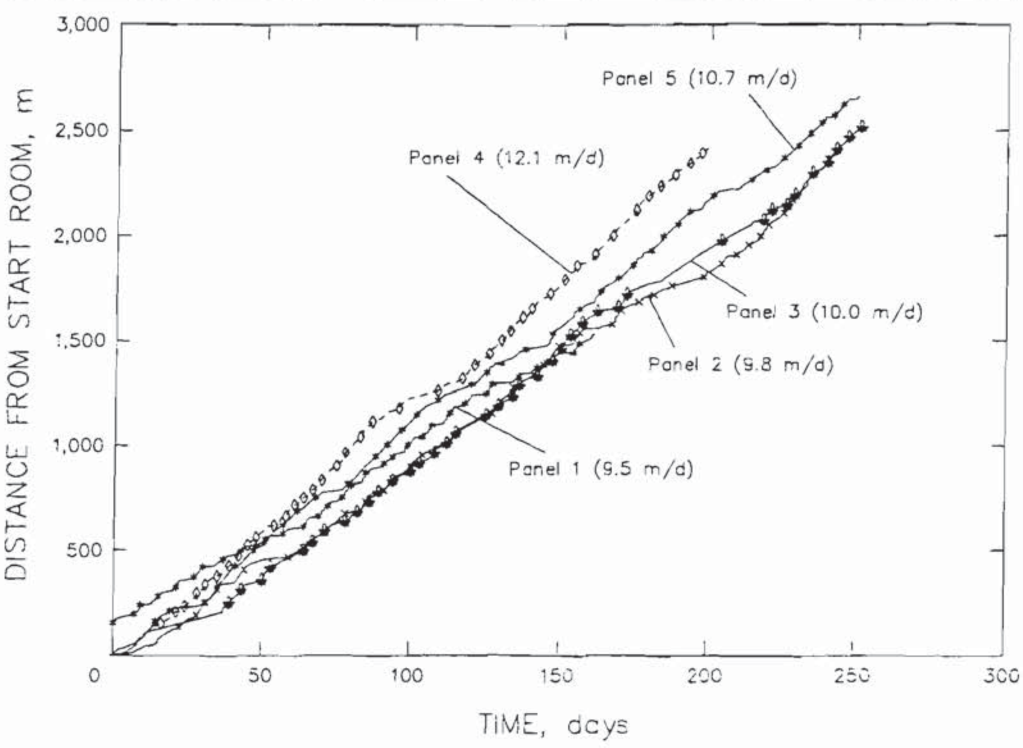


Figure 8
Layout of Typical Gate Road Instrument Site.

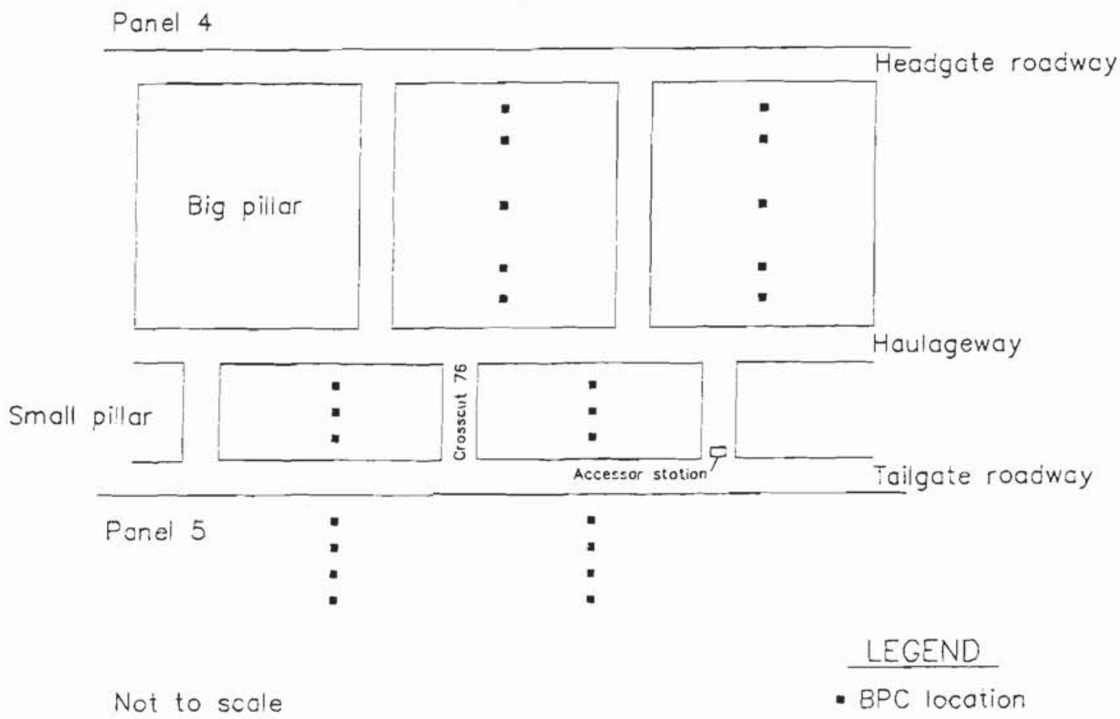


Figure 9
Shield Pressure Monitoring Locations Along Each Longwall Panel Face.

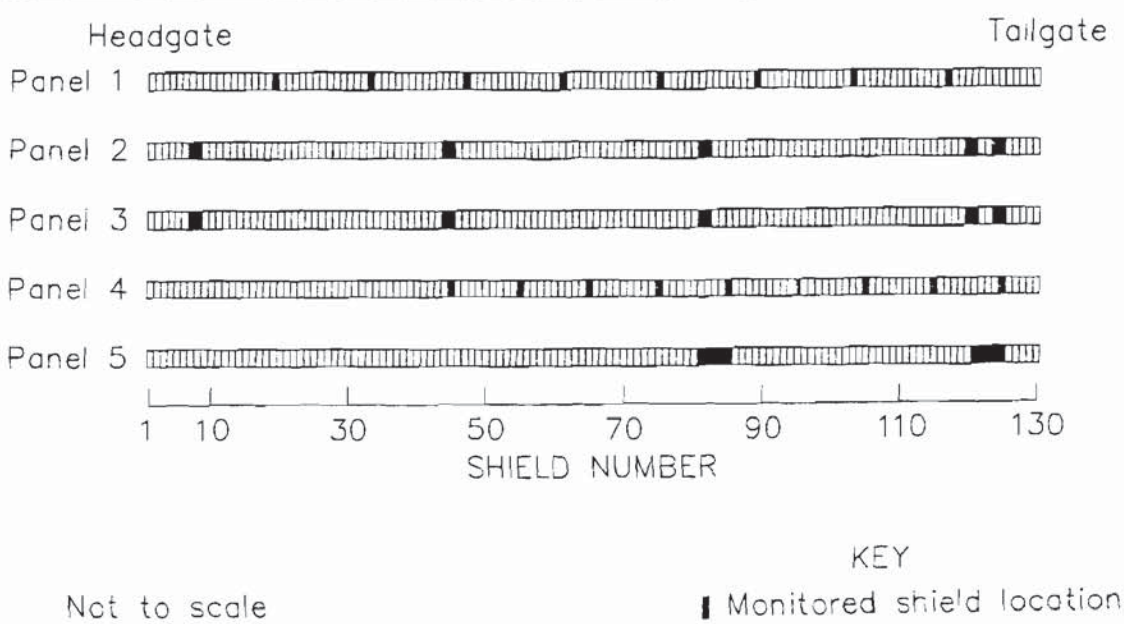
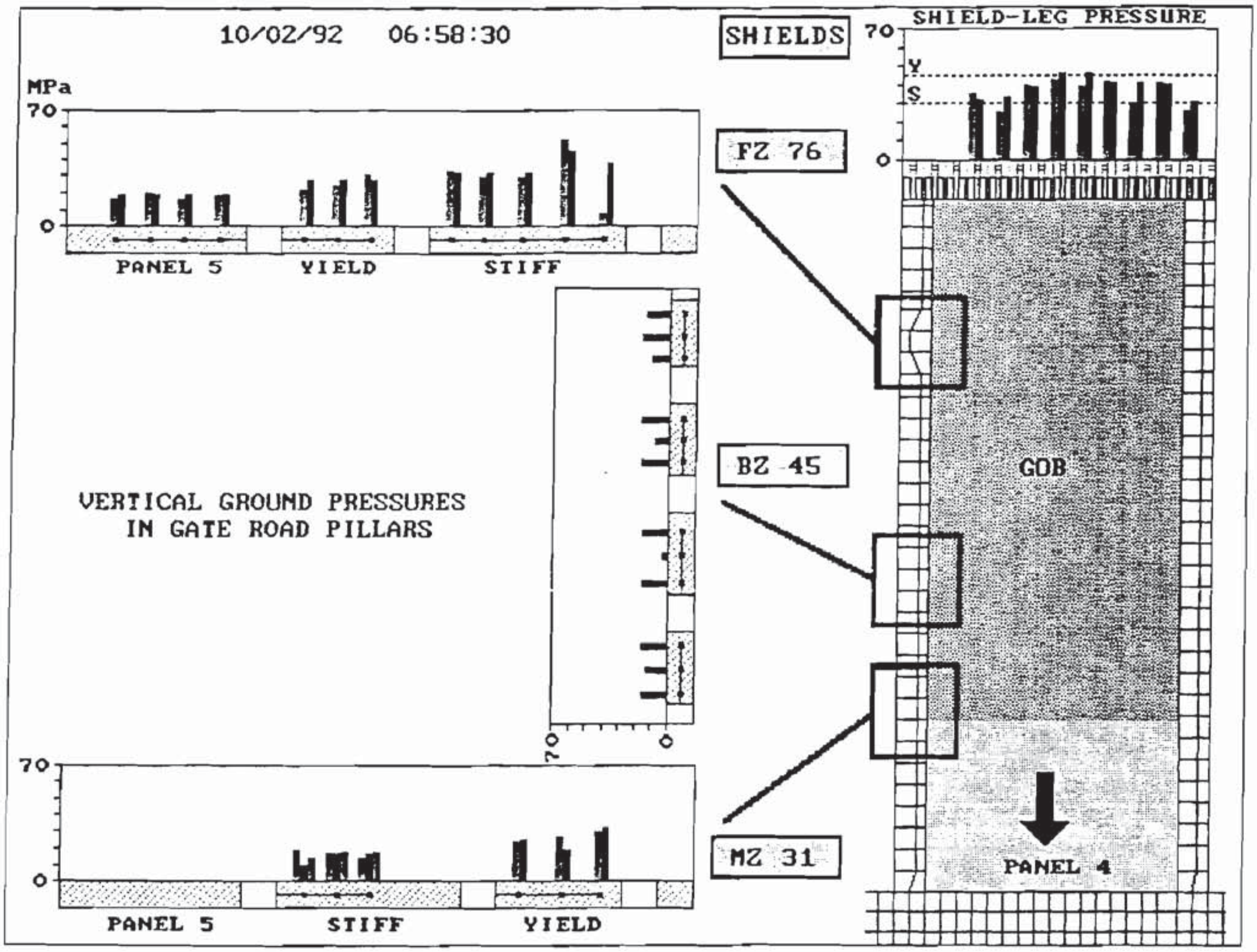


Figure 10
Typical Computer Display of Real-Time GCMS Data.

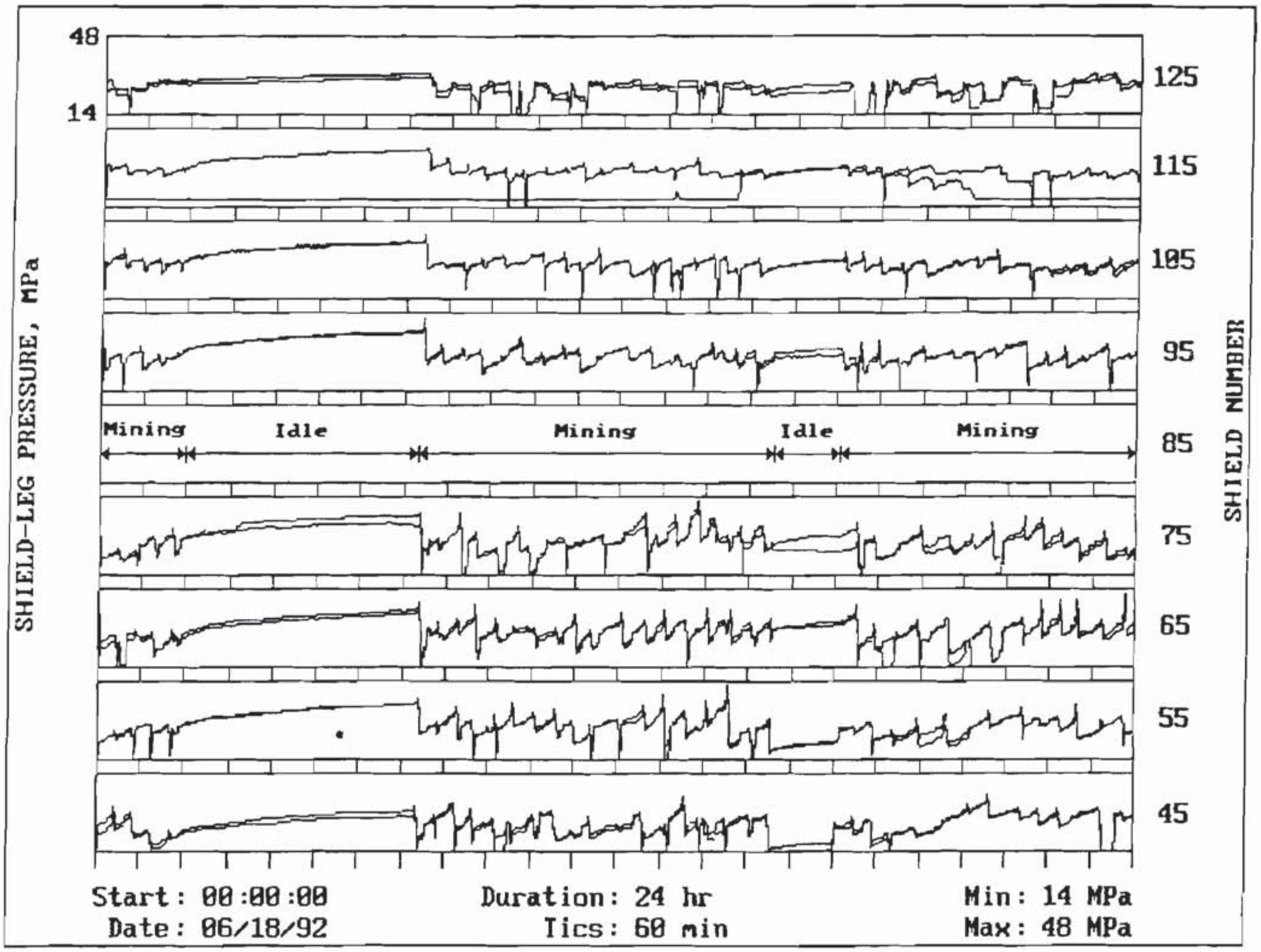


SHIELD AND PILLAR LOADING PATTERNS

To date, the GCMS has been used to collect, store, process, analyze, and evaluate field data from five longwall panels. Typical shield loading as a function of mining cycle time is shown in figure 11 for a typical work day. Normal shield duty cycles for each mining cut across the longwall face usually vary between 30 and 45 min. Longer duty cycles, varying from hours to days, occur during breakdowns, between shifts, and over idle periods such as weekends and vacations. Generally, shield loads continue to increase during these longer cycles, as shown in figure 11, often approaching the yield load of the shields within a few hours. During panel 1 mining, the face typically experienced heavy spalling across the face during the initial cut of a work shift after the face had been idle for several days. The mine subsequently altered its production schedule to reduce the duration of idle periods and now schedules at least one longwall production shift per day (*10*).

Panel-wide shield-loading behavior was analyzed by reducing the shield pressure data for evaluation by calculating the time-weighted average pressure (TWAP) for each shield duty cycle that corresponded to each 0.75-m

Figure 11
Computer Display of Typical Shield-Loading Behavior.



cut (about 30 in) across the face. The TWAP is assumed to be representative of the average support pressure of each shield for each mining cut. The difference between the TWAP and the setting pressure (SP) for each duty cycle (TWAP-SP) has also been calculated to evaluate the behavior of the shields. The TWAP-SP represents the variation in shield loading during a duty cycle. Figure 12 illustrates the typical variations in both the average TWAP and the average TWAP-SP across the longwall face during an operating shift. Although the TWAP distribution is relatively uniform, the TWAP-SP distribution shows significantly greater shield-loading variations in the central portion of the longwall face. Three-dimensional plots of the TWAP data for panels 2 and 3 are shown in figure 13. A review of the data indicates that the average shield pressure tends to be about 3.5 MPa (500 psi) higher in the tailgate third of the panel. The analysis also indicates that the average shield pressure near the headgate roadway is approximately equal to the setting pressure of the shields. This finding suggests that the face area near the headgate edge of the panel is typically protected from high ground pressures by the structural integrity of the headgate roadway pillar system.

Anomalous shield-loading patterns have been observed in association with catastrophic ground failure events at the test mine, such as major roof caves and/or abrupt tailgate roadway closures. Anomalous shield loading was first detected while analyzing the shield data collected during the initial roof caving of panel 2. As shown in figure 14, pressure on the four midpanel shields increased rapidly to yield pressure during two consecutive cycles several hours before the initial roof cave. Also, note that shield pressures did not relieve after the cave but remained at the yield pressure until the shields were advanced at the start of the next shift (*10*).

Anomalous shield loading has also been indicative of catastrophic tailgate roadway ground failures, typically referred to as "floor bumps" by the miners. As shown in computer displays of shield loading behavior presented as figures 15, 17, 20, 21, and 22, the midpanel shields appear to experience greater-than-normal pressure increases during consecutive mining cycles for about 3 to 6 h preceding the occurrence of a tailgate floor bump, whereas the near-tailgate shields experience a rapid increase in pressure several minutes before or during the occurrence of a floor bump. This phenomenon has been designated as a shield pressure "bump signature" that is associated with the occurrence of all known tailgate floor bumps monitored at the test mine.

During the mining of panel 2, a significant tailgate floor bump occurred near gate road instrument site 6L-74 (figure 6) at about 10:30 p.m. on October 18, 1990. A computer display of shield loading behavior during this event is shown in figure 15 and corresponds to the characteristic bump signature previously described. Figure 16 is a computer display of ground pressure changes monitored in the adjacent instrumented gate road pillar site. An analysis of these data indicates a series of increasingly severe ground failures over a period of about 6 h, which culminated in a severe floor bump around 10:30 p.m. The tailgate roadway was closed for the remainder of the shift, and mining did not resume until the tailgate roadway supports were replaced two shifts later.

Three additional floor bumps were monitored during the mining of panel 2 in the vicinity of gate road instrument site 6L-40 (figure 6). Figure 17 is a computer display of shield-loading behavior monitored during the first of these floor bumps reported by the miners to have occurred about 1 p.m. on January 29, 1991, at crosscut 6L-41. The characteristic bump signature is very evident in the plot of the shield pressure data shown in figure 17. Figure 18 is a computer display of the gate road ground pressure changes monitored during the same floor bump. These data show significant ground pressure increases in the pillar site located approximately 45 m (150 ft) outby the longwall face at the time of the floor bump. Figure 19 is a computer display of gate road ground pressure changes associated with the second floor bump that occurred on January 31, 1991, at crosscut 6L-40 adjacent to the instrument site. These data indicate abrupt failure of both the pillar and panel coal ribs adjacent to the tailgate roadway to a depth of at least 6 m (20 ft) inside the original entry rib line. Shield pressure data were not being collected at this time because of problems with the trunk line serving the longwall face instruments. The third significant floor bump occurred as the face passed through crosscut 39 on February 6, 1991, at about 4:45 p.m. just prior to the start of the evening production shift. The characteristic bump signature is very evident in the computer display of the shield pressure data shown in figure 20.

During the mining of panel 3, at least five consecutive tailgate floor bumps occurred as the longwall face passed through crosscuts 44, 43, 42, 41, and 40 during November of 1991 (figure 6). The characteristic bump signature was evident in shield pressure data for each of these events, as shown in figure 21, which is presented here as a representative computer display of panel 3 data. Three of these floor bumps caused severe damage to the tailgate roadway support structures (cribs and posts) outby the face, resulting in cessation of mining operations until re-support of the roadway could be effected.

A similar set of data was collected for floor bump events that occurred during the mining of panel 4 (figure 6). Each of the tailgate floor bumps monitored during the mining of panel 4 produced the same characteristic floor bump signature, as shown by the example computer display presented as figure 22.

Figure 12
Average Values of TWAP and TWAP-SP Variations Across Longwall Face.

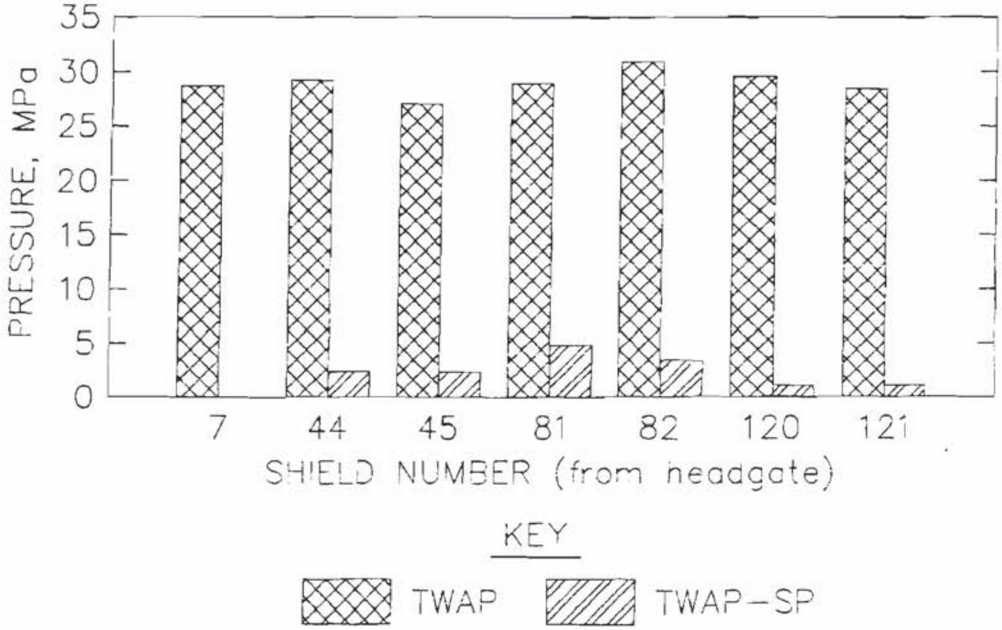


Figure 13
Three-Dimensional Plot of Panel-Wide TWAP Data.

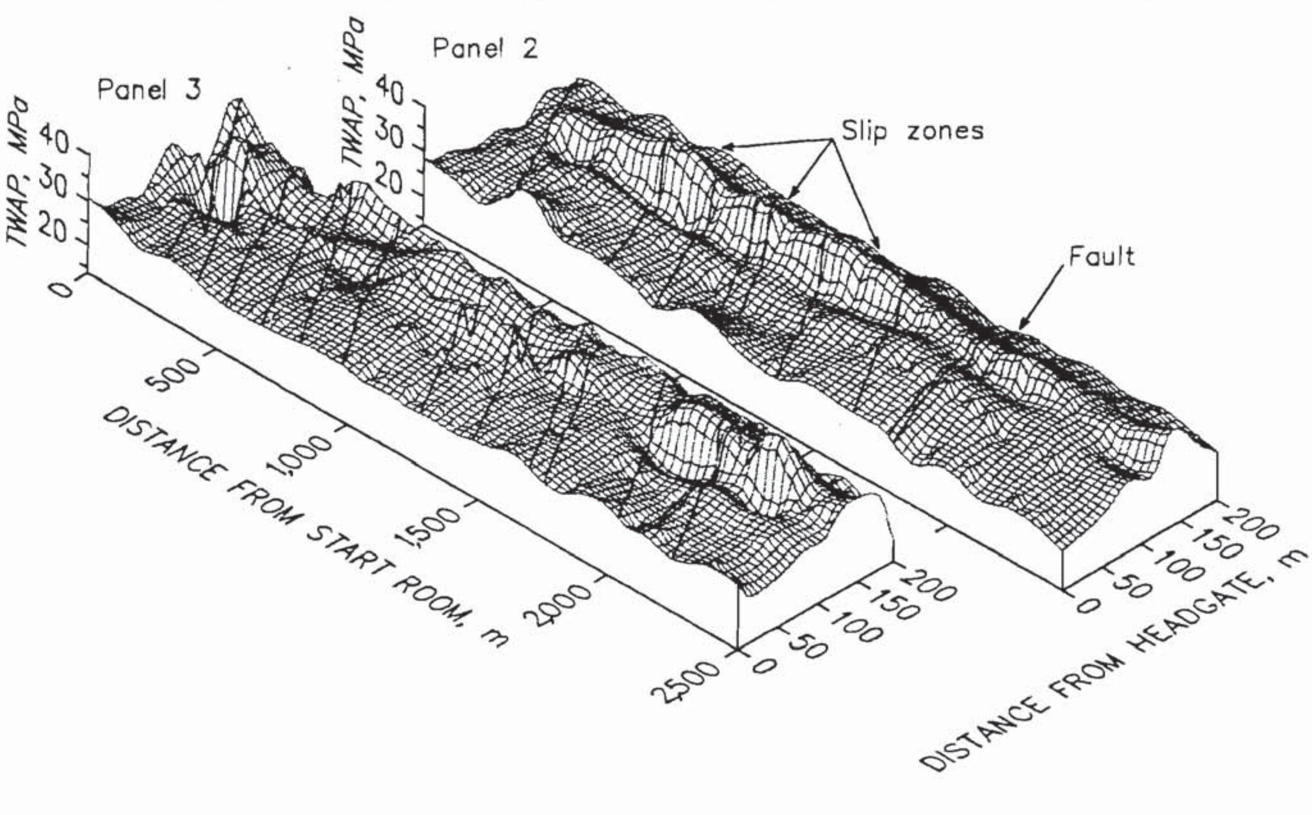


Figure 14
Computer Display of Shield-Loading Behavior Associated With Panel 2 First Cave.

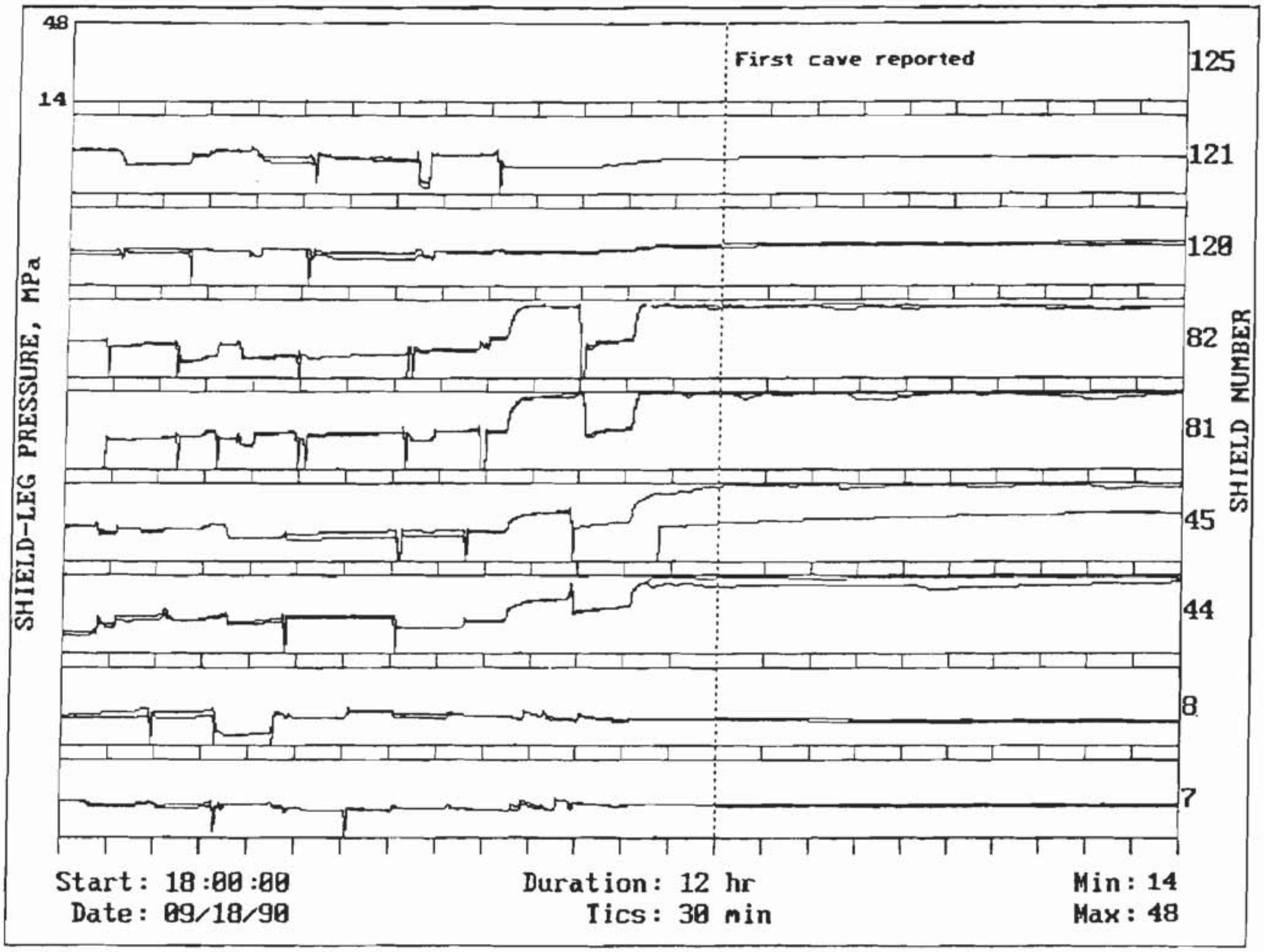


Figure 15
Computer Display of Shield-Loading Behavior Associated With Catastrophic Floor Bump Near Panel 2 Tailgate Roadway Instrument Site 6L-74.

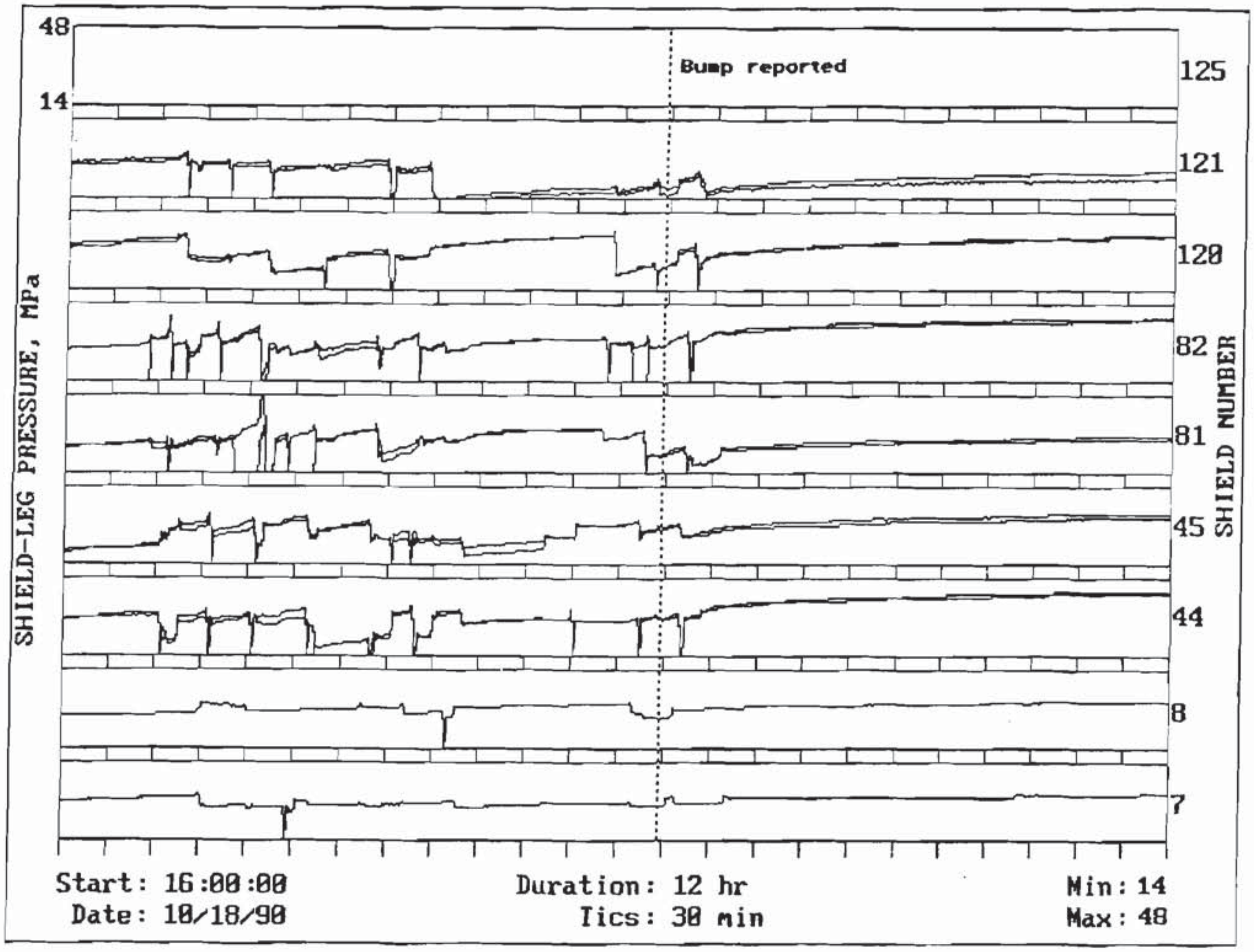


Figure 16
Computer Display of Ground Pressure Changes Associated With Floor Bump Monitored at Instrument Site 6L-74.

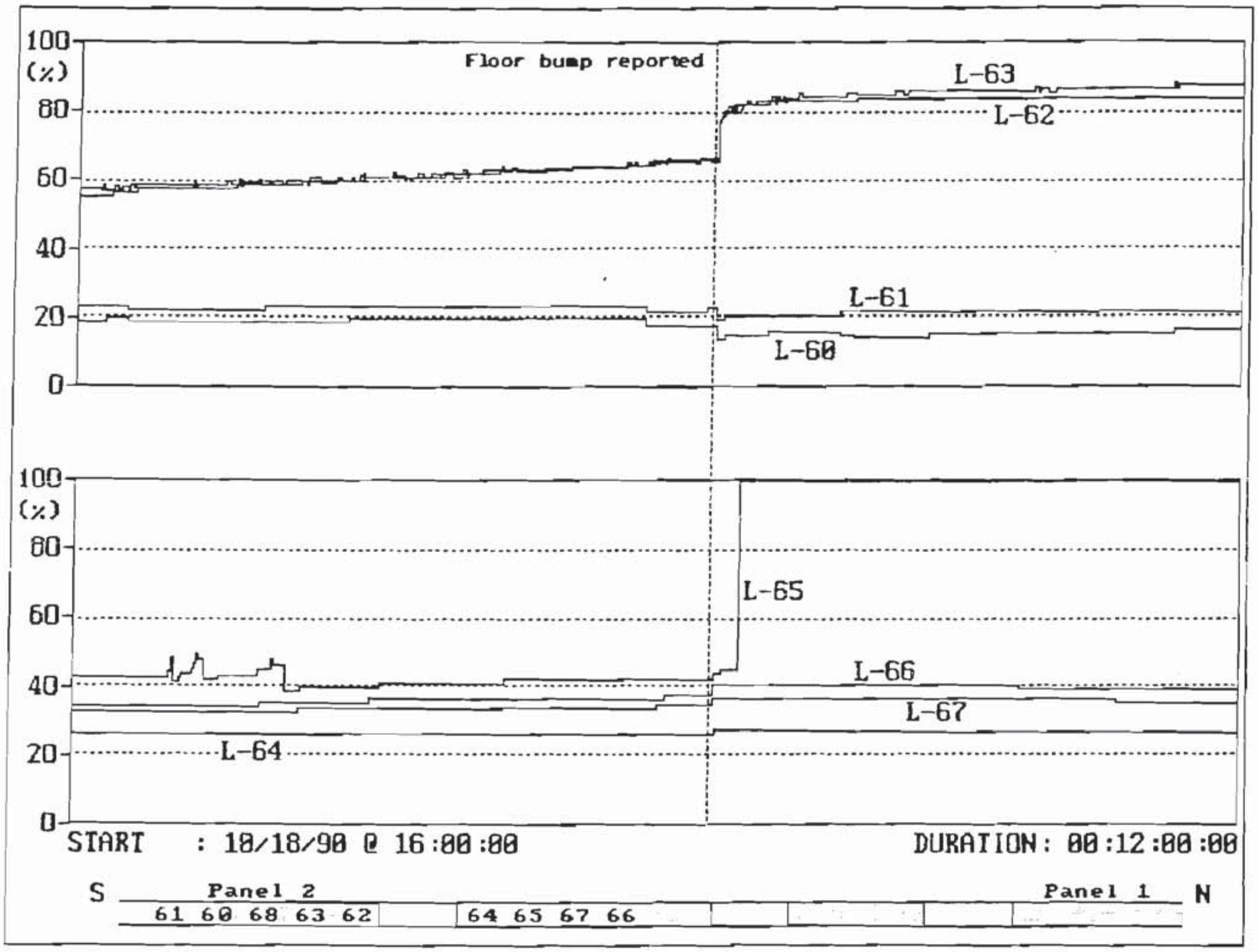


Figure 17
Computer Display of Characteristic Signature Plot of Shield-Loading Behavior During Floor Bump Monitored at Crosscut 6L-41.

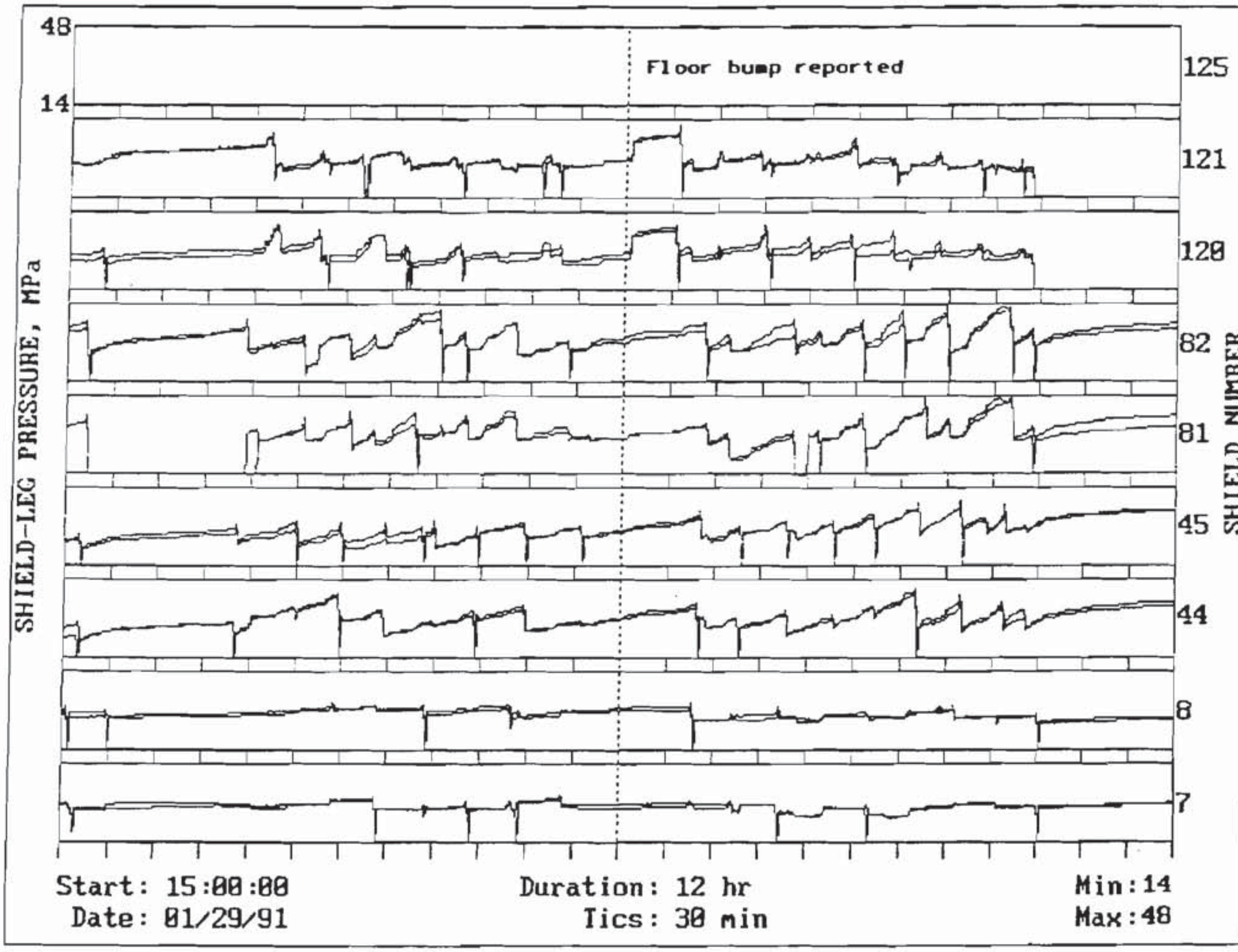


Figure 18
Computer Display of Gate Road Ground Pressure Changes Monitored During Floor Bump at Crosscut 6L-41.

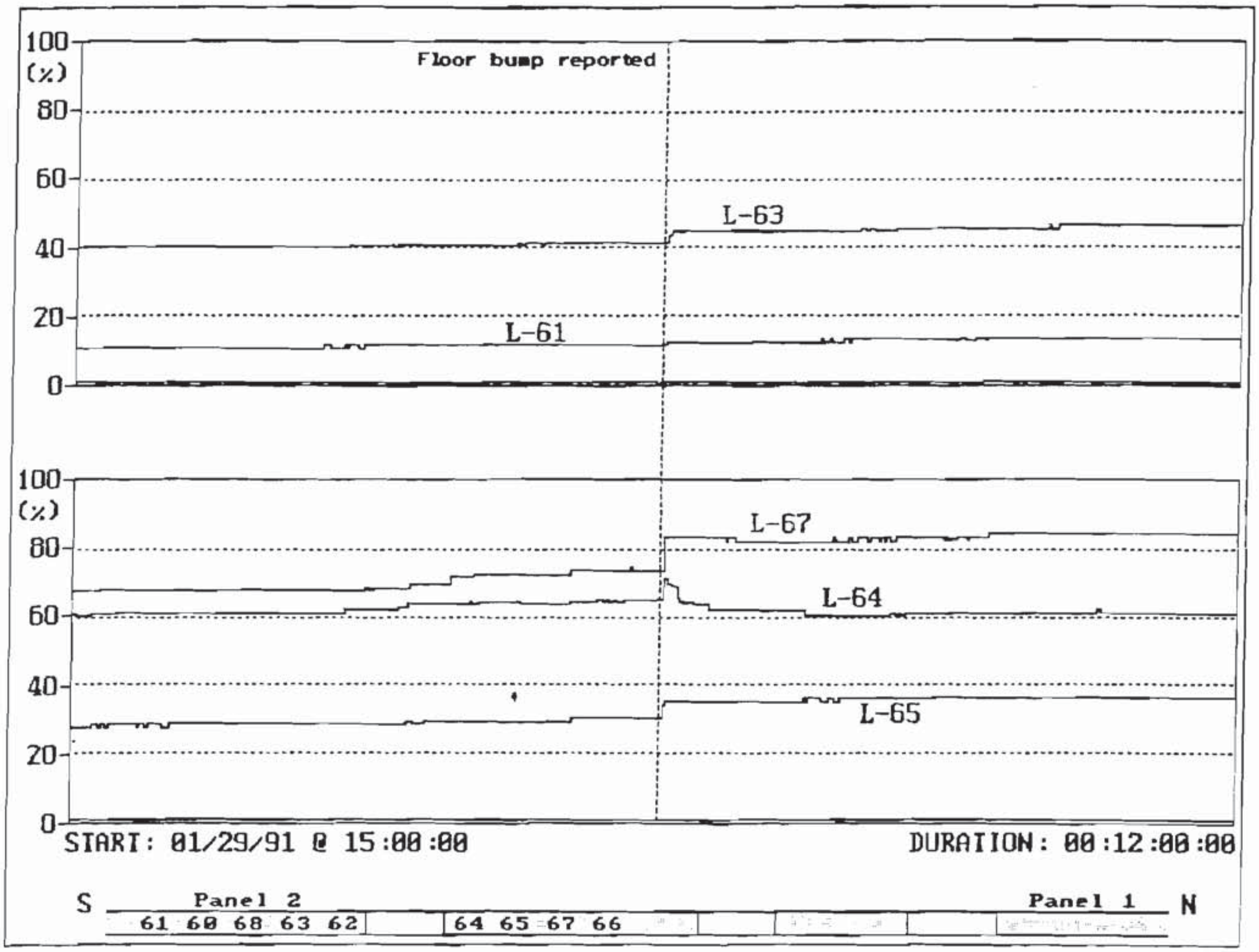


Figure 19
Computer Display of Ground Pressure Changes Associated With Floor Bump Monitored Adjacent to Instrument Site 6L-40.

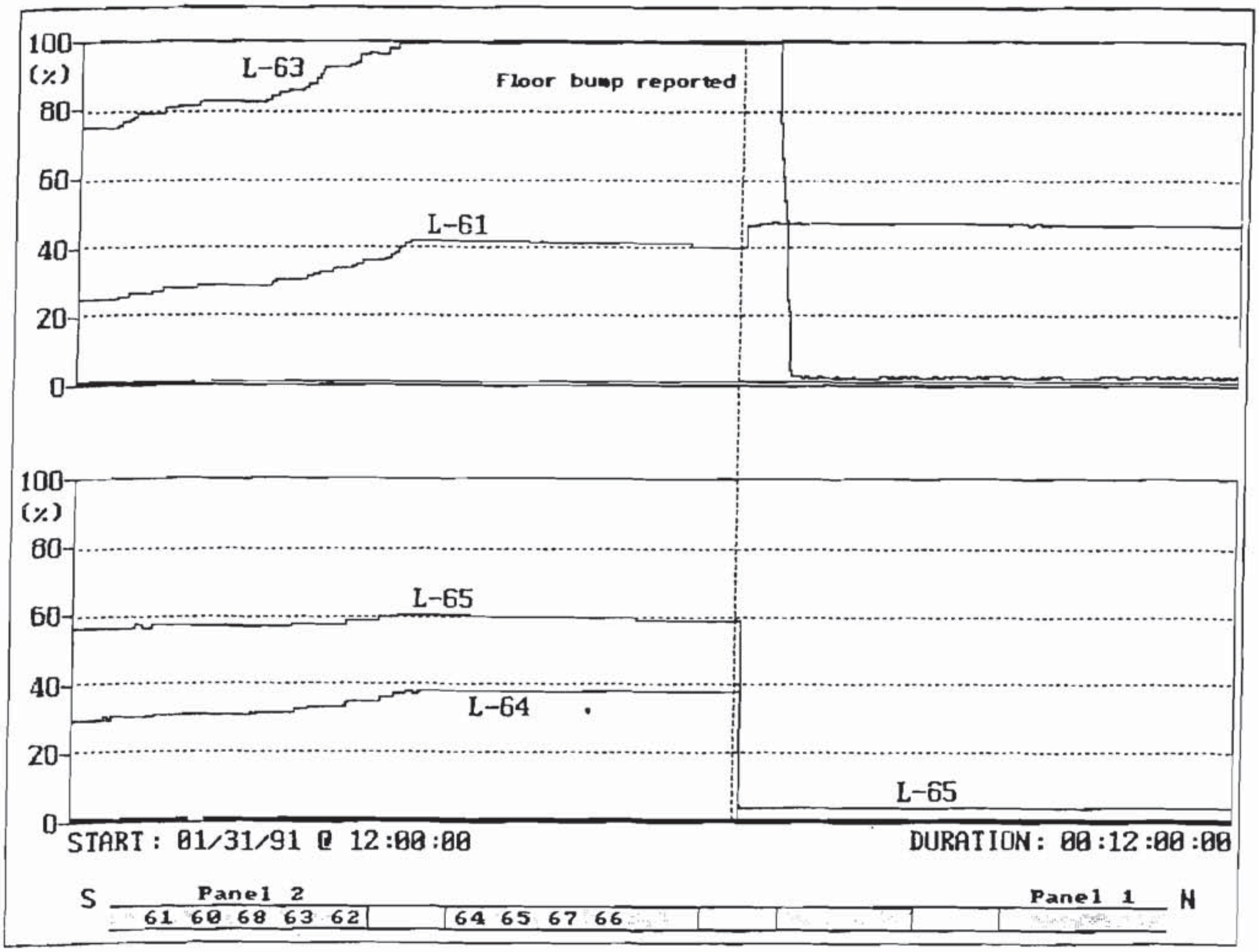


Figure 20
Computer Display of Characteristic Signature Plot of Shield-Loading Behavior During Floor Bump Monitored at Crosscut 6L-39.

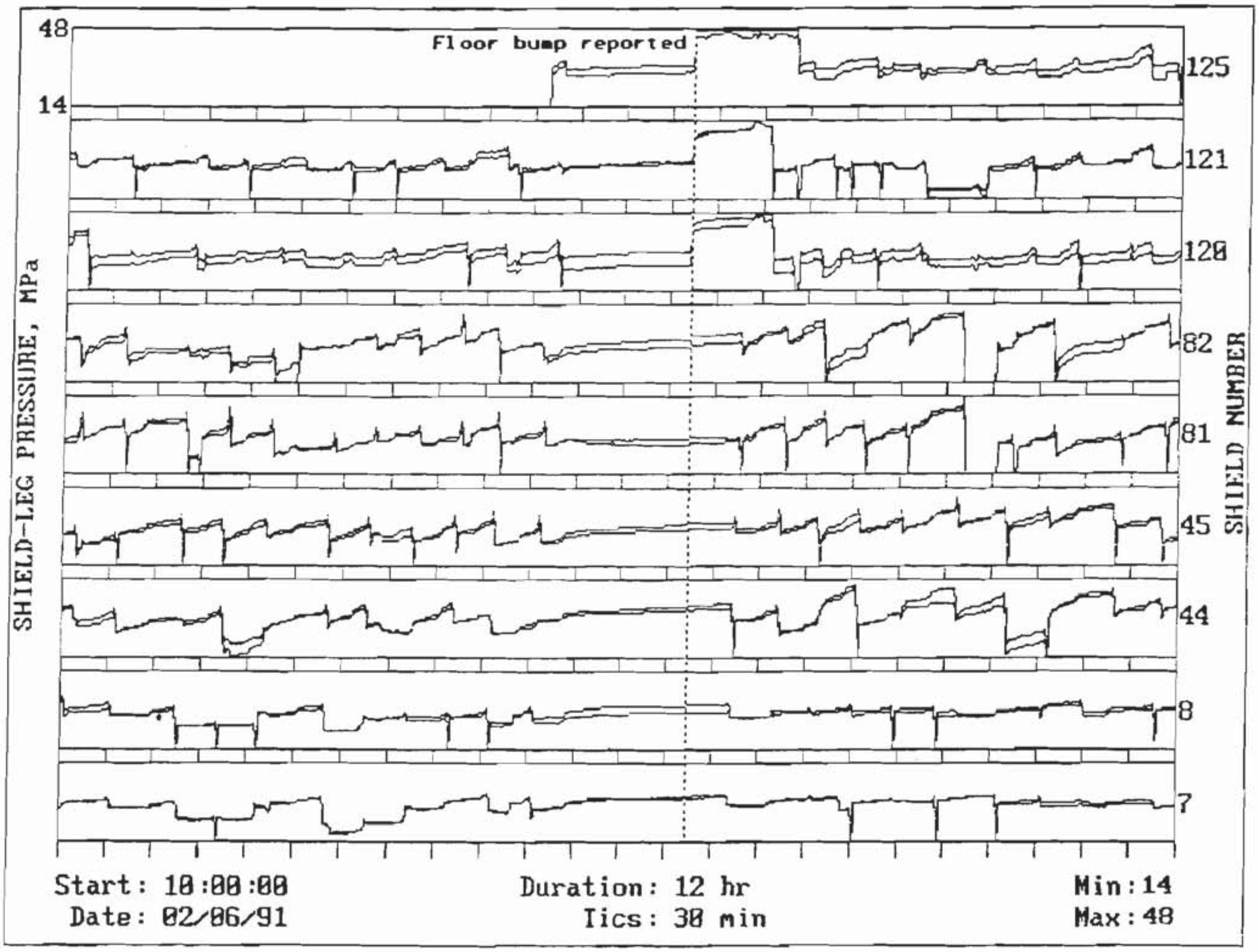


Figure 21
Representative Computer Display of Panel 3 Shield-Loading Behavior During Tailgate Roadway Floor Bumps.

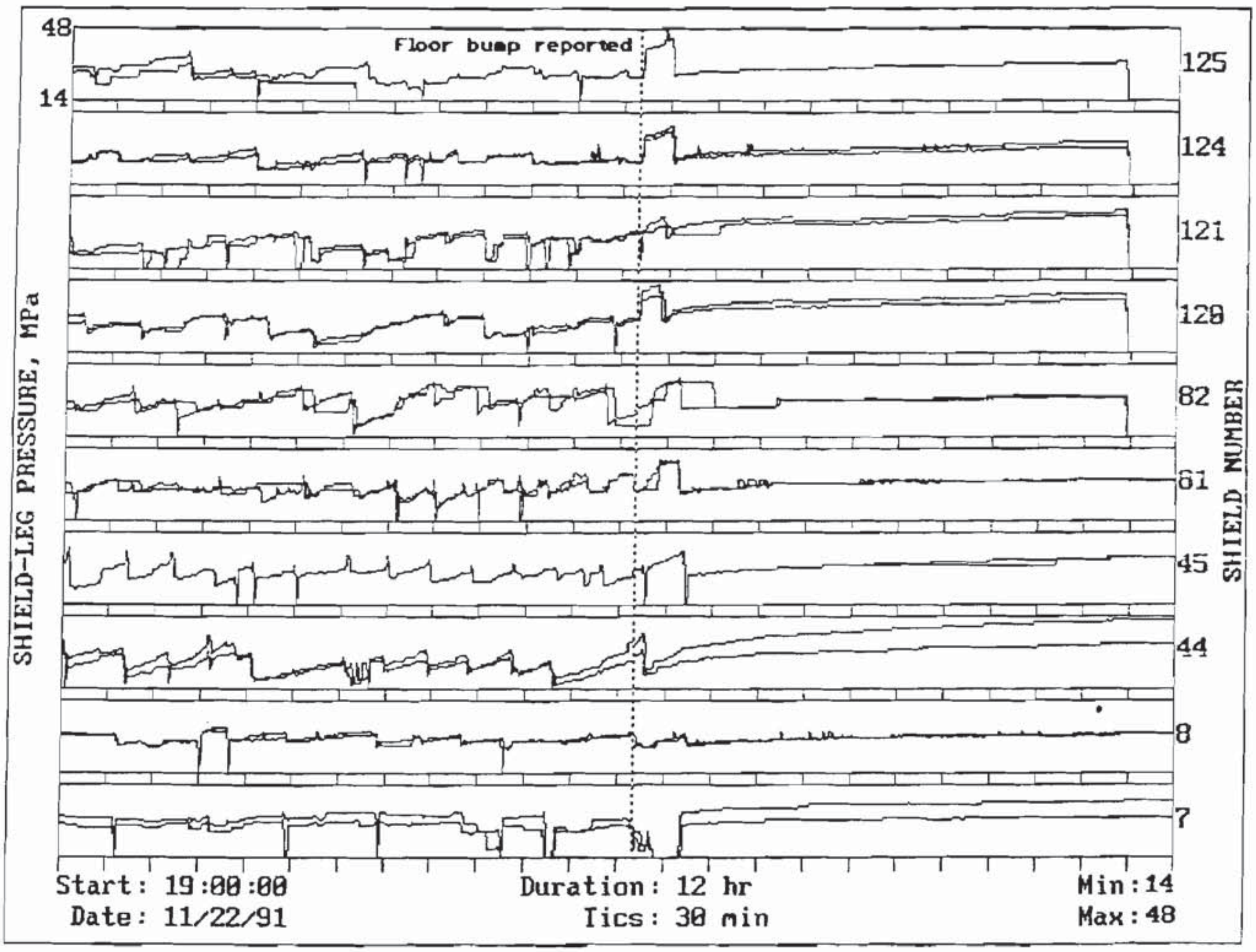
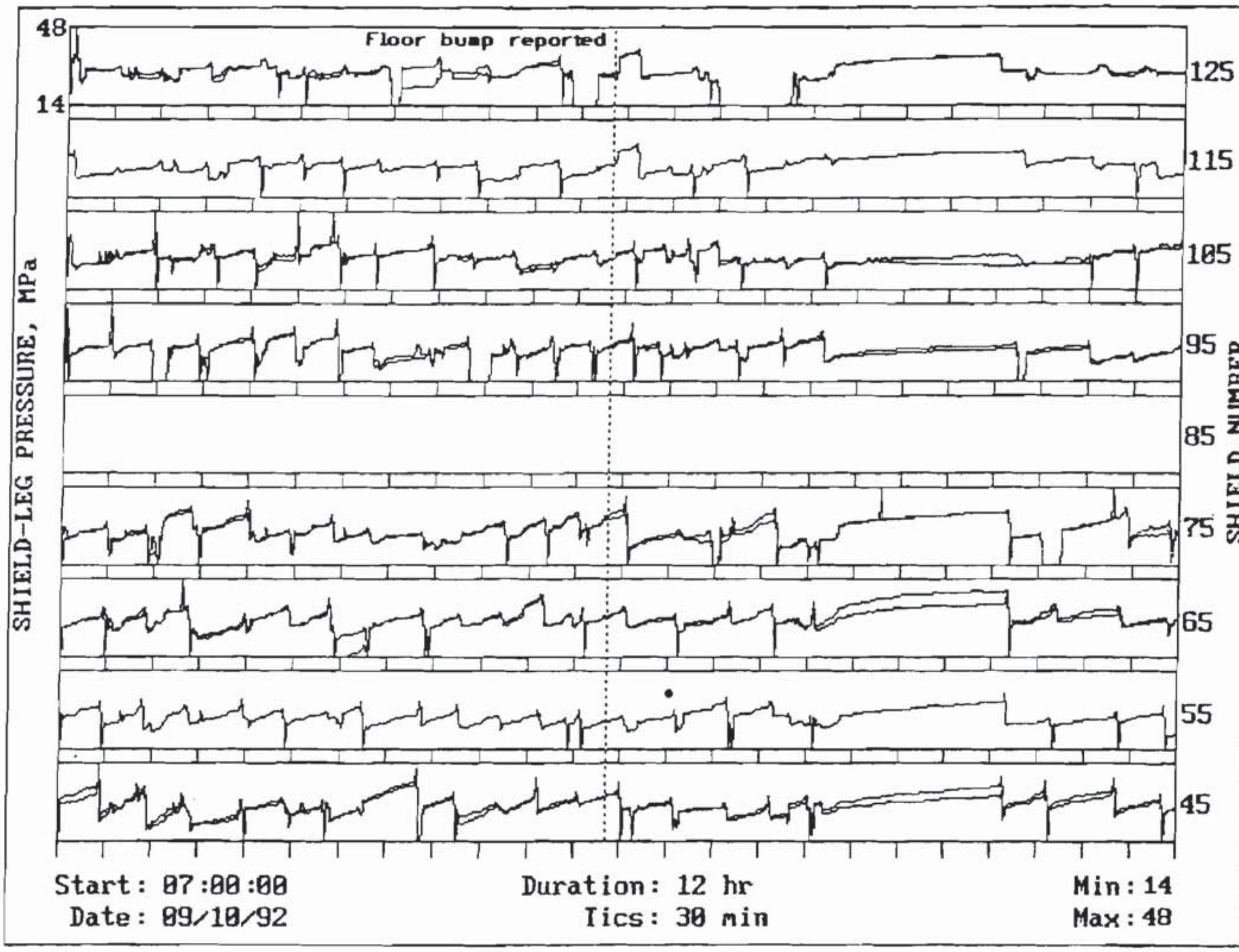


Figure 22
Representative Computer Display of Panel 4 Shield-Loading Behavior During Tailgate Roadway Floor Bumps.

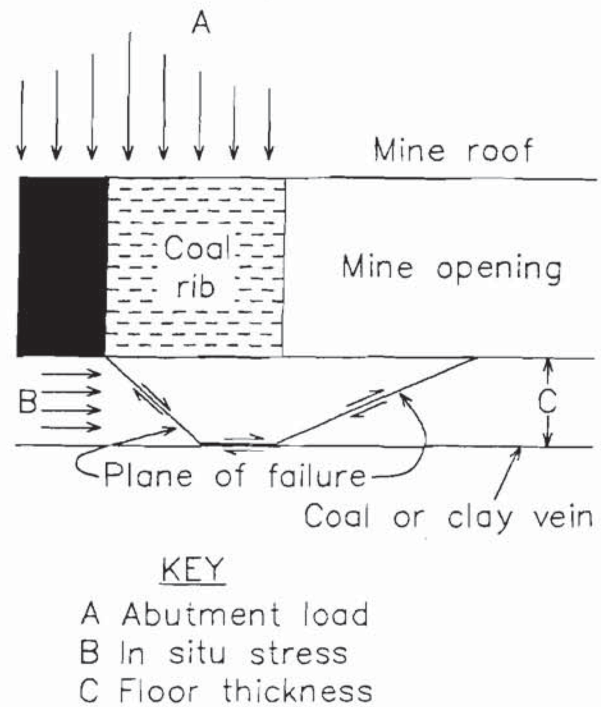


MECHANISM OF TAILGATE ROADWAY GROUND FAILURES

In-mine observations and analyses of available rock mechanics data indicate that the major pressure abutment zones surrounding the longwall panels extend at least 36 m (120 ft) beyond the limits of coal extraction from each of the panels. The sequential extraction of longwall panels has created overlapping abutment zones in the regions enclosing the gate road pillar systems left between the panels. This mining method has created a "pillar-line point" known to be conducive to catastrophic failures in bump-prone ground (*13*). The overlapping pressure abutments apparently overload the pillars left between the panels and create excessive ground pressures, which are a contributing factor related to the cause of the abrupt floor bump phenomenan being observed during the extraction of the longwall panels at the test mine. It was observed that the floor bumps always occurred as the tailgate of the longwall face was passing by an adjacent tailgate roadway crosscut forming, essentially, a four-way intersection. Upon reflection, it is obvious that this would be the location of the greatest ground stress buildup in and around the longwall panel.

The catastrophic tailgate roadway closures typically involved instantaneous floor heave associated with rib spalling and pillar sloughing for a distance of approximately 25 m (80 ft) outby the active face (*14*). In general, the floor bump problem is believed to be related to stiff floor rock conditions. It has been observed that when the tailgate ground conditions are "soft" and roadway convergence is in the range of 15 cm (0.5 ft) or more, catastrophic failure of the tailgate floor and adjacent pillar does not occur. However, when the tailgate ground conditions are "stiff" and entry closure is less than 10 cm (0.4 ft) at the tailgate, catastrophic gate road ground failures usually occur as the face passes through the roadway crosscut. The catastrophic ground failures are usually severe enough to dislodge support structures (i.e., cribs and props) and shut down face operations until the roadway ground structures can be repaired or replaced. In the bump-prone regions of the mine, the immediate floor consists of a relatively strong bed of thin sandstone underlain by a much weaker layer of interbedded coal and clay stringers. This weak layer forms the initial failure plane for the abrupt failure and extrusion of the immediate floor from beneath the adjacent coal ribs when the instantaneous floor heave and associated rib sloughing occur, as shown schematically in figure 23 (*15*). Thus the relative thickness and strength of the immediate floor strata are thought to be the critical factors in determining the relative stability of the tailgate roadway as it is subjected to the increasing ground pressures of the abutment zone created by the retreating longwall panel. Several methods of preventing and/or controlling the floor bumps were devised to facilitate the safe and efficient operation of the longwall panels. Destress blasting of the immediate floor of the tailgate roadway was adopted as being one of the most effective methods of preventing abrupt tailgate floor heave (*15*) and was used successfully to prevent serious floor bump problems during mining of the fifth longwall panel at the test mine.

Figure 23
Schematic of Floor Bump Failure Mechanism.



SUMMARY AND CONCLUSIONS

The use of the computerized GCMS to monitor shield-loading behavior and gate road pillar pressure changes continuously has significantly improved understanding of ground behavior during the high-speed extraction of longwall panels using mechanized mining equipment. Much has been learned about the abutment load transfer phenomenon as it relates to gate road stability. The demonstrated correlations between variations in shield pressure and ground failures (i.e., floor bumps and major roof caves) offer mining engineers the first real possibility of developing a real-time alarm system to anticipate impending ground failures associated with high-speed mechanized longwall mining systems. Analyses of anomalous shield pressure data and catastrophic ground failure events associated with these anomalies suggest that shield pressures may be used as precursors of impending ground hazards associated with the high-speed mechanized extraction of longwall panels in underground coal mines. The data indicate that these precursors may precede ground hazard events by several minutes to several hours, thus allowing the mine operator the time needed to take the appropriate action to protect mine workers and prepare for the installation of additional strata support. This early warning capability clearly indicates the need for a continuous monitoring program.

The GCMS provides a continuous flow of geotechnical data from the operating longwall panel. The GCMS is rapidly evolving into a knowledge-based expert system incorporating automatic data collection and analysis techniques that can function both as a real-time ground stability evaluation tool and provide historical data for future mine design and mine planning studies.

REFERENCES

1. Merritt, P. C. Annual Longwall Census. Coal Min. (formerly Coal Age), February issues, 1983 to 1994.

2. Cox, R. M. The Use of a Graphic Mini-Computer System as a Rock Mechanics and Roof Support Design Tool. Paper in Proceedings of the Second Conference on Ground Control in Mining, ed. by S. S. Peng and J. H. Kelley (Morgantown, WV, July 19-21, 1982). Dep. Min. Eng., WV Univ., Morgantown, WV, 1982, pp. 159-170.

3. McDonnell, J. P., R. M. Cox, and J. P. Dunford. Automated Monitoring and Geotechnical Evaluation for Ground Control in Longwall Mining. Paper in New Technology for Longwall Ground Control - Proceedings: U.S. Bureau of Mines Technology Transfer Seminar, comp. by C. Mark, R. J. Tuchman, R. C. Repsher, and C. L. Simon. USBM Spec. Publ. 01-94, 1994, pp. 131-145.

4. Jackson, D. Deserado Gains Edge Through Computer Monitoring. Coal Min., v. 24, No. 12, Dec. 1987, pp. 31-45.

5. Zaburunov, S. A., and A. P. Sanda. Mine Monitoring in America. Coal, v. 24, No. 6, June 1988, pp. 34-40.

6. Barrett, P. British Boost Longwall Efficiency Through Monitoring and Control. Coal, v. 24, No. 6, June 1988, pp. 44-47.

7. Ostermann, W. Utilization of Data Transmission in Modern Mining. Paper in Proceedings of the 8th International Conference on Coal Research (Tokyo, Japan, Oct. 16-20, 1988). 1988, pp. 51-65.

8. Deguchi, G., A. Fukushima, and K. Nishimura. Integrated Monitoring for the Prediction of Outbursts. Paper in the Proceedings of the 8th International Conference on Coal Research (Tokyo, Japan, Oct. 16-20, 1988). 1988, pp. 66-80.

9. Garrity, P., and K. W. Mills. Intelligent Longwall Support Management Systems. Paper in Computer Systems in the Australian Mining Industry (Queensland, N.S.W., Australia, Sept. 1989). CSIRO Div. of Geomech., Univ. Wollongong, Queensland,N.S.W., Australia. 1989, pp. 152-158.

10. Hanna, K., K. Haramy, and T. R. Ritzel. Automated Longwall Mining for Improved Health and Safety at the Foidel Creek Mine. SME preprint No. 91-165, 1991, 8 pp.

11. Conover, D., and K. Hanna. Shield Pressure Monitoring To Detect Longwall Ground Control Hazards. Paper in Proceedings, Forth Conference on Ground Control for Midwestern U.S. Coal Mines, ed. by Y. P. Chungh and G. A. Beasley (Mt. Vernon, IL, Nov. 2-4, 1992). Dep. Min. Eng., S. IL Univ., 1992, pp. 217-226.

12. Hanna, K., and R. Cox. Automated Ground Control Management System for Coal Mine Hazard Detection. Paper in Proceedings of the Second International Symposium on Mine Mechanization and Automation, ed. by G. Almgren, U. Kumar, and N. Vagenas (Lulea Univ. of Tech., Lulea, Sweden, June 7-10, 1993). Balkema, 1993, pp. 681-689.

13. Holland, C. T., and E. Thomas. Coal-Mine Bumps: Some Aspects of Occurrence, Cause and Control. USBM Bull. 535, 1954, 37 pp.

14. Cox, R. M. Tailgate Roadway Convergence: A Key Indicator of Potential Ground Control Problems. Paper in Proceedings of the 13th International Conference on Ground Control in Mining, ed. by S. S. Peng (Morgantown, WV, Aug. 2-4, 1994). Dep. Min. Eng., WV Univ., Morgantown, WV, 1994, pp. 185-189.

15. Buchan, G. M., and R. M. Cox. Cause and Control of Longwall Floor Heave. Paper in Proceedings of the Longwall U.S.A. International Exhibition & Conference (Pittsburgh, PA, June 7-9, 1994). Maclean Hunter, Ormand Beach, FL, 1994, pp. 165-172.

Special Publication 01-95

Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines

Edited by Hamid Maleki, Priscilla F. Wopat, Richard C. Repsher, and Robert J. Tuchman

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea L. Graham, Director

Library of Congress Cataloging in Publication Data:

Maleki, Hamid N.

Proceedings : mechanics and mitigation of violet failure in coal and hard-rock mines / edited by Hamid Maleki ... [et al.].

p. cm. — (USBM special publication; 01-95)

Includes bibliographical references.

Supt. of Docs. no.:I 29.151 : 01-95.

1. Rock bursts—Congresses. 2. Mine roof control—Congresses. 3. Coal mines and mining—Safety measures—Congresses. 4. Mines and mineral resources—Safety measures—Congresses. I. Title. II. Series: Special publication (United States. Bureau of Mines); SP 01-95.

TN317.M35 1995 622'.28—dc20 95-7138 CIP