MICRO-SEISMIC METHOD OF DETERMINING THE STABILITY OF UNDERGROUND OPENINGS

By Leonard Obert and Wilbur I. Duvall
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THE STABILITY OF UNDERGROUND OPENINGS

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Introduction

THE CRACKING AND POPPING of rock, often heard by men working underground, for years has been interpreted as a warning of danger and unstable ground. However, not until 1939 was it discovered that rock under stress generates subaudible and sometimes audible seismic disturbances (referred to as "micro-seisims"), which can be detected with the use of a suitable seismic apparatus. Since that date laboratory and field investigations have been in progress to ascertain to what extent this phenomenon can be utilized to detect, localize, and determine the magnitude of areas of instability in and around mine openings and to predict if and when failure will occur. These investigations have included a determination of the types of problems to which the method is applicable and the effect of rock type, geological defects, such as joints, fractures, faults, and other uncontrollable factors, on the reliability of results.

Six reports have been prepared covering the investigations conducted between 1940 and 1952. These reports describe some of the characteristics of micro-seisims, as determined from both laboratory and field tests; the equipment used to pick up and record micro-seisims; the general test procedure and method of analyzing results; and applications of the method to specific mining problems.

This report contains a summary of the investigations conducted between 1940 and 1955. The characteristics of micro-seisims and the micro-seismic equipment are briefly reviewed. Generalizations regarding experimental procedure and analysis of results are presented. Examples of the various types of mining problems to which the micro-seismic method is applicable are cited, and the results of a few specific investigations are discussed.

1 Work on manuscript completed April 1966.
2 Chief, Applied Physics Laboratory, Division of Mineral Technology, Bureau of Mines, College Park, Md.
3 Physicist, Applied Physics Laboratory, Division of Mineral Technology, Bureau of Mines, College Park, Md.
4 "Micro-seisim"—used herein to describe small-scale-seismic disturbances—not to be confused with "microseism."
5 Micro-seisim is the adjective corresponding to the noun micro-seisim.
6 Italicized numbers in parentheses refer to items in the bibliography at the end of this report.
ACKNOWLEDGMENTS

Investigations have been conducted in the following mines: Ahmeek, Ahmeek, Mich. (Calumet & Hecla, Inc.); Cliffs-Shaft, Ishpeming, Mich., and the Athens and Mather, Negaunee, Mich. (The Cleveland-Cliffs Iron Co.); See-Sah, Webber Nos. 1 and 2, West Side, South Side, Wilbur, Barr, Beaver, and Gordon (The Eagle-Picher Co., Cardin, Okla.); Lucky Bill, Baxter Springs, Kans. (Federal Mining & Smelting Co.); Southern, Treece, Kans. (Federal Mining & Smelting Co.); Woodchuck, Baxter Springs, Kans. (Weidman Mining Co.); Lawyer, Picher, Okla. (Lawyers Zinc & Lead Mining Co.); Lake Shore, Kirkland Lake, Ontario (Lake Shore Mines, Ltd.); Frood, Copper Cliff, Ontario (International Nickel Co.); No. 1, Mascot, Tenn. (American Zinc Co.); Leadwood, Leadwood, Mo. (St. Joseph Lead Co.); Miami, Miami, Ariz. (Miami Copper Co.); Magma, Superior, Ariz. (Magma Copper Co.); Harmony and Old Bed, Mineville, N. Y. (Republic Steel Corp.); King, Hiawatha, Utah (U. S. Fuel Co.); Jonathan, Zanesville, Ohio (Pittsburgh Plate Glass Co.); Sunshine, Kellogg, Idaho (Sunshine Mining Co.); Bible No. 7 stope, Zinc Mines Works, Jefferson City, Tenn. (Tennessee Coal & Iron Division, United States Steel Corp.); and Experimental Oil-Shale, Rifle, Colo. (Federal Bureau of Mines).

Some of the investigations conducted in these mines were made at the request of the company; the remainder were initiated by the Bureau of Mines to obtain additional information on the applicability of the method to regional mining problems. The authors gratefully acknowledge the cooperation of these companies and their officials in making available their facilities for this research.

The authors also acknowledge the assistance given by numerous Bureau of Mines employees who have assisted in one phase or another of these investigations.
CHARACTERISTICS OF MICRO-SEISMS

The process by which micro-seisms are generated is not known. Rocks under pressure in the laboratory generate a large number of micro-seisms before any visible sign of failure is evident and a much larger number after crushing and fracture occur. In underground mines micro-seisms are generated both before and concurrently with the occurrence of visible cracking. Thus, the magnitude of the ground movement necessary to produce micro-seisms does not have to exceed the elastic displacements produced in rock under stress. The smaller disturbances probably are caused by no more than the failure of the bond between individual mineral components, while the larger ones likely are caused by cracking and fractures, which may range from cracks just visible to the unaided eye to rock bursts.

Both laboratory and field tests have shown that for a given state of stress the micro-seismic production varies widely with rock type. Breccias, conglomerates, and rocks containing large crystalline components, such as coarse granite, usually are the most productive, whereas sedimentaries and fine-grained metamorphic rocks are least productive. However, all rocks strong enough to core with a diamond drill will produce micro-seisms to some extent. Data obtained indicate that in large bodies of rock micro-seisms also originate at the interfaces of joints, fractures, and faults.

Laboratory tests have shown that when rocks are stressed in a hydraulic press the micro-seismic rate, that is, the number of micro-seisms generated per unit time, increases with the applied load (8). Some rocks produce micro-seisms when the applied load is only 20 percent of the ultimate compressive strength of the specimen; all rocks produce micro-seisms when loaded to 60 percent of their ultimate strength. The increase in the rate is most pronounced as the ultimate strength is approached; for example, in some tests the rate increased more than a hundredfold between 60 and 90 percent of the ultimate strength. Also, laboratory tests showed that the micro-seismic rate varied with the rate of change of stress—the higher the rate of change, the higher the micro-seismic rate. This variation was true for both increasing or decreasing stress changes, although much more pronounced for the former. These experiments are discussed in detail in Bureau of Mines Report of Investigations 3803.

Field tests have shown that the magnitude of individual micro-seisms decreases as the distance from the point of origin to detection is increased; the smallest micro-seisms travel only a few feet before they become too weak to detect, whereas large disturbances such as those produced by visible cracking can be detected in hard rock at distances of several thousand feet. Rock bursts in the Lake Shore mine, Kirkland Lake, Ontario, have been recorded by the seismograph at Weston, Mass. (3). High-speed oscillographic photographs of micro-seismic wave trains show that the pulse duration ranges from 0.004 to 0.1 second. The frequency characteristics of the pulse have not been determined accurately because they are affected by the geophone characteristics. (See p. 3.) However, as the pulses propagate through the rock the high-frequency components in the pulse are absorbed more strongly than the low-frequency components. By listening with headphones to the amplified output of geophones, this effect is pronounced enough to give a rough estimate of travel distance of the pulse.

MICRO-SEISMIC EQUIPMENT

Although the micro-seismic equipment has been revised almost continually, the fundamental procedure for detecting and recording micro-seisms (7) has remained unchanged. A photograph of a late model of the micro-seismic equipment is shown in figure 1. Briefly, the equipment is a geophone (electro-mechanical transducer) for converting vibrations in the rock into corresponding electrical pulses. (See fig. 2.) The generating element in the geophone is a piezoelectric (Rochelle salt) crystal mounted as an undamped cantilever, with a resonant frequency of 1,000 cycles per second (c. p. s.). The geophones are about 1¾ inches in diameter and 8 inches long so that they can be placed in drill holes to contact solid rock. They are connected to an amplifier by means of a shielded geophone cable. The amplifier is a
conventional three-stage unit having a maximum gain of approximately 100,000. (See fig. 3.) Headphones can be plugged into the amplifier to provide for aural reception. The output from the amplifier is compressed to a range of 10 to 1. The compressed signal is rectified and filtered to form a single pulse. This pulse is further amplified by a power stage and then recorded with a magnetic writer on a dry-paper (Teledolos) tape. A photograph of the recorder is shown in figure 4 and representative records in figure 5. The recording tape is driven with a synchronous motor usually at a speed of 3 inches per minute. The recorder can be operated for 16 hours without reloading. Time marks are introduced onto the record every 2 minutes. This recording unit and system of amplifiers comprise a single channel; usually two of these channels are incorporated into a single case. These units operate from a 110-volt, a.-c., 50-60 or 25-cycle power supply. A time switch is included in the power supply so that the equipment can be programed for a weekly schedule.

For some investigations it is not necessary to make a graphic recording; rather, an analysis can be made from aural reception. For this purpose only the three-stage amplifier unit is required, which is usually a portable battery-operated unit.

**Figure 1.**—Micro-seismic Equipment.

A, Program switch; B, power supply; C, 2-channel amplifier and graphic recorder; D, calibrator.

**Figure 2.**—Micro-seismic Geophone.
Figure 3.—Micro-seismic Amplifier.

Figure 4.—Micro-seismic Recorder.

Figure 5.—Representative Micro-seismic Records.
Upper, Record from 2 geophones 50 feet apart showing coindicences (marked A); lower, record from 2 geophones in same test hole showing nearly complete coincidence.
TEST PROCEDURE

In applying the micro-seismic method to specific mining problems a number of factors must be considered before selecting a proper test procedure. These factors include type of problem, configuration of the mine structure, accessibility of the area to be tested, seismic properties of the rock and ore, selection of recording periods, etc.

In general, the problems to which this method is applicable can be divided into four types:

1. Detecting stress areas or, sometimes equally important, the absence of stress areas.
2. Localizing and delineating affected areas.
4. Estimating if and when failure will occur.

DETECTING STRESS AREAS

Detection of areas of stress involves no more than placing a geophone in the suspected area and listening to or recording the micro-seismic activity. If no micro-seismims are detected, the area can be considered stable; if micro-seismims are detected, the geophone is in or near a stress area. The procedure assumes that the rock under test, if stressed, will generate micro-seismims. However, as previously pointed out, no exceptions have been found in the coring class of rock (7). Although this test is simple, its importance should not be overlooked; in most of the investigations made to date the problem has been to determine whether or not a suspected area, such as a mine pillar, brow, or roof arch, was stable.

LOCALIZING AND DELINEATING AFFECTED AREA

If micro-seismims are detected, the next problem is to find the center and extent of the affected area, a procedure which can be effected by a number of means. Because the micro-seismic rate decreases with the distance from the point of origin, the operator can probe from point to point with a single geophone until the area producing the maximum micro-seismic rate and hence the center of the disturbance is located. Although the recording type of equipment is generally used for this test, comparatively small areas of instability, such as would be encountered in roof-trimming operations, can be localized by aural testing.

Micro-seismic rates also can be used to localize a stress area by placing a number of geophones in the area at fixed positions and comparing the recorded micro-seismic rates from each. The geophone nearest the center of disturbance will pick up the highest micro-seismic rate; the geophone next closest to the area, the next highest rate, etc.

Because the amplitude of a micro-seismin decreases with the distance from the source, comparison of the average amplitudes, as received from a number of points, can be used as a basis for localizing the point of origin. This can be accomplished either by probing with one geophone or employing a number of geophones at fixed points. In either instance, the amplitude comparison should be made from a recording.

Similarly, the affected area may be localized by comparing the amplitude of a single micro-seismim at various points, rather than taking the average amplitudes of a group. The simultaneous reception and recording of a single micro-seismim from two or more geophones (referred to as a coincidence) requires the use of multichannel recording. Comparison of individual amplitudes is possible with the recording type of micro-seismic equipment previously described because the recording tapes are driven synchronously.

Finally, the area can be localized by comparing the fraction of coincident and noncoincident recordings, as received from each of a number of geophones. For example, suppose that one geophone is planted close to the center of the disturbance and a second geophone at some distance therefrom. Geophone 1 will pick up all the micro-seismims picked up by geophone 2 (coincidences) plus an additional number of insufficient intensity to travel the additional distance (noncoincidences). Where a number of geophones are used, the one closest to the source will pick up the greater number of noncoincidences. Examples of records showing coincident and noncoincident micro-seismims are shown in figure 5.

In general, probing methods are employed whenever the area under investigation is easily accessible, whereas comparison of micro-seismic rates or amplitudes from a group of geophones is employed to obtain data on inaccessible areas—areas where it might be difficult to drill holes for the placement of geophones.
The micro-seismic method of detecting and localizing areas of stress is a relatively quantitative procedure. No particular experience on the part of the operator either with respect to placement of geophones or interpretation of the data is required.

ESTIMATING MAGNITUDE OF STRESS AND PREDICTING FAILURE

Estimating the magnitude of stress and determining if and when failure will occur are qualitative procedures that depend on the operator’s familiarity with the load vs. micro-seismic rate relationship for the various rock types and on an analysis of structural problems, the normal stress pattern for various-shaped mine openings. Some indication of the load vs. micro-seismic rate relationship can be obtained by observing rock specimens in a hydraulic press and noting the corresponding micro-seismic rate \( (8) \). Additional information can be obtained by inducing small-scale failures in mines, such as roof falls, and noting the micro-seismic rate before and during the process. One informative test that usually can be effected in an operating mine is to plant geophones near a heading or bench round and to note the increase in the maximum micro-seismic production after the blast. This micro-seismic production results from the working of the rock and the readjustment of stress and is characteristic of the rock type. The readjusting period is usually of short duration so that after 15 to 30 minutes the micro-seismic rate decreases to a value no greater than that preceding the blast.

Estimating stress and predicting failure from micro-seismic data would be difficult if it were not for the fact that the micro-seismic rate increases substantially with increases of stress. For example, in normally stable rock structures the micro-seismic rate may be of the order of 0 to 10 micro-seismims per hour, distant mining operations may double or triple the rate, and local mining operations may increase it tenfold to a hundredfold. These increases usually cease when mining operations are stopped. However, for stress conditions that indicate failure, micro-seismic rates in excess of 100 per minute are common. These high rates usually precede failure long enough (from 24 hours to several weeks) to adequately warn the workmen. Sometimes a high rate may be detected for a period without being followed by failure; again, sporadic occurrence of high micro-seismic production may persist, sometimes for several weeks, before failure occurs. In any event, any area that has produced high micro-seismic rates must be considered relatively unstable.

When the micro-seismic method is used to determine the structural stability of underground openings, the operator should have some understanding of the state of stress and the areas of maximum stress concentration that would exist in an ideal structure, that is, one composed of homogeneous and isotropic rock. Information on this subject can be obtained from stress theory and/or model studies \( (I, 2) \). Usually geophones are planted in areas of high stress concentration so that the first indication of stress load can be detected. Also, if areas of inscability are detected at points other than those indicated by theory or model studies, the cause should be investigated.

If structural studies are to be made over large areas and for extended periods, geophones should be installed for the duration of the tests at a number of points within the area. The spacing of the geophones depends primarily on the seismic conductivity of the rock. Some information on the seismic conductivity of a given rock type can be obtained from “hammer blow” tests. For rock of good conductivity a light blow with a 1-pound hammer can be picked up by a geophone at distances of 500 to 1,000 feet, but both the hammer blow and the geophone must be on “solid” rock. For rock of this quality (which would include most of the rocks that will open stope) geophones are usually spaced on 100- to 200-foot centers.

Most mining operations, such as drilling, blasting, mucking, trampling, hoisting, and pumping, produce seismic disturbances that are picked up and recorded with the micro-seismic equipment. These man-made disturbances complicate, if not obscure, interpretation of normal micro-seismic records. In general, records must be made when the mine is not operating; that is, between shifts or off shift. Some minimum disturbances, such as distant pumping or hoisting, can be tolerated because the seismic records therefrom are usually periodic and uniform in amplitude, whereas the micro-seismic records are always random both in time and amplitude. For the detection of small-scale stress areas, such as loose rock, several recording periods or listening tests are made daily. For structural studies a 1- or 2-hour recording period is sufficient to evaluate day-to-day changes.
APPLICATION OF MICRO-SEISMIC METHOD

The following case histories illustrate the application of the micro-seismic method to: (a) Detect "loose" in mine roof, that is, for roof control; (b) determine the stability of underground openings; and (c) study rock-burst problems.

ROOF CONTROL

The removal of small pieces of partly detached rock, usually termed "loose," by barring, trimming, or scaling is a common practice in all underground mines. Larger sections of rock are usually shot down or supported with stulls or props if they are considered unsafe. However, the degree of safety of a suspected area is usually based on personal judgment and, as the size of the area increases, the decision to leave, remove, or support becomes correspondingly more difficult.

During the past 15 years the micro-seismic method has been employed in a number of mines to detect loose. In most instances, these roof-control investigations have been made in connection with more general structural studies. Examples of several applications follow.

INVESTIGATION IN ZINC MINE

Roof control was studied for approximately a year in the Zinc Mines Works, Tennessee Coal & Iron Division, United States Steel Corp., Jefferson City, Tenn. This zinc mine is made up of large lenticular deposits, which occur in comparatively massive limestones and dolomites. The deposit is mined by open stoping with random pillars. The roof rocks are usually limestone or dolomite. A number of geophones were placed in the roof of a large stope to ascertain the effect on the general stability of the roof arch as pillars were removed. During the course of this investigation it was noted that the geophones in the roof were sensitive to local areas of disturbance. An inspection of the roof disclosed loose areas which, when removed, caused the micro-seismic activity to decrease notably. This practice was ultimately developed into a routine roof-control procedure. To improve the control, the roof trimmer and his helper became familiar with the operation of the micro-seismic equipment to the extent that, before the start of the shift and during the lunch-hour period when drilling and other machinery was not operating, the helper would listen to the response from the various geophones in the roof. When micro-seismic activity was noted, the roof trimmer would bar down the area until the section of rock causing the activity was located and removed.

INVESTIGATION IN IRON MINE

A micro-seismic investigation was conducted for a period of approximately 1½ years in the Old Bed mine (Clonan workings), Republic Steel Corp., Mineville, N. Y. The principal objective of this investigation was to determine the stability of the roof arch overlying an area from which pillars were being removed. Incidental to the main objective of this investigation, sections of loose rock in the roof and pillars were detected and localized before failure (9).

The Clonan workings lie in a large anomalous fold, which forms a complete loop. The ore is virtually pure magnetite. The roof rock is a granitic gneiss, which is separated from the ore by a sharp contact. The area was mined by open stoping with random pillars. The stope height was over 100 feet in the area in which this test was performed. Geophones were installed at fixed positions in the roof and side walls of the stope adjacent to a large pillar, which was in the process of being removed. Daily micro-seismic observations showed that the average micro-seismic rate was approximately 8 micro-seismins per hour. This is the so-called background rate. The removal of pillar ore and other mining in the area did not change this rate, indicating that the general stability of the arch over the stope and the stress over the roof arch and side walls was unaffected by this mining.

Approximately 4 months after this investigation was begun, the micro-seismic rate in one of the roof geophones jumped from an average of 8 per hour to over 1,800 per hour, an increase of over two-hundred-fold. Sometime within the next 12 hours a 4-ton slab fell from the roof. The micro-seismic data obtained from this geophone is given in table 1. The other geophones in this stope were unaffected by this small disturbance. Both the degree of localization and the magnitude of the increase in the micro-seismic rate are characteristic of roof falls of this size.
The micro-seismic rate varied erratically during this period. From July 12 to 20 the rate rose from 8 to over 2,000 per hour, where it remained until July 22, when a small fall occurred. It dropped to less than 200 on July 23 and 24 and then rose to the 2,000 range again on July 25, 26, and 27. On July 28 the rate dropped to 540 per hour, although no fall preceded the decline; on July 29 it returned to the 2,000 range, and the large fall occurred. However, the rate continued to increase on July 30 (to 2,640 per hour) and then dropped rapidly and did not rise again during the remainder of the investigation. This erratic behavior is quite characteristic of local areas of stress; in fact, it has been found that in local zones the micro-seismic rate often would rise to a comparatively high level and fall without any visible evidence of failure. However, this cycle usually recurs until there is some type of failure, followed by a short period of readjustment during which the micro-seismic rate decreases (sometimes in an erratic manner) until the stresses have become equalized and the micro-seismic rate returns to its background level.

**OTHER INVESTIGATIONS**

Similar roof-control investigations have been made in a hard iron-ore mine in northern Michigan, in both jasper and argillaceous shale roof; in a number of mines in the Tri-State zinc district, in chert breccia and limestone roof; and in the Oil-Shale mine, Rifle, Colo., in marlstone roof. All of these investigations supplemented more general studies of the mine structure. In most instances, both recording and aural testing were employed. Loose sections of roof ranging from less than 1 ton to over 250 tons were detected before failure.

**STABILITY OF UNDERGROUND OPENINGS**

Most of the micro-seismic investigations conducted to date have been concerned with the structural stability of underground openings, that is, the stability of relatively large rock masses, such as mine pillars, roof arches, and stope walls. Most of these investigations have been made in open-stope mines or mines in which the stopes require no artificial support. Because large areas are involved and because the changes in rock stress are observed over extended periods (from 1 month to several years), recording-type equipment has been employed.

Structural stability investigations can be divided into two classes. In the first the stope is normally stable, but changes in the stress pattern are induced by continued mining. The micro-seismic rate in stable ground is very low (usually of the order of 10 micro-seisms per

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**Table 1.—Micro-seismic rate in 112 area, hole 13, April 28 to May 2**

<table>
<thead>
<tr>
<th>Record</th>
<th>Date</th>
<th>Micro-seismic rate 1 per hour</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>101B</td>
<td>Apr. 28</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>102B</td>
<td>Apr. 29</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>103B</td>
<td>Apr. 30</td>
<td>1,800</td>
<td>Above normal. 4-ton roof fall followed this record.</td>
</tr>
<tr>
<td>104B</td>
<td>May 1</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>105B</td>
<td>May 2</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

1 Averaged over 2-hour period.

**Table 2.—Micro-seismic rate in 112 area, hole 3, July 12 to August 9**

<table>
<thead>
<tr>
<th>Record</th>
<th>Date</th>
<th>Micro-seismic rate 1 per hour</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>193B</td>
<td>July 12</td>
<td>10</td>
<td>Normal background rate.</td>
</tr>
<tr>
<td>201B</td>
<td>July 17</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>202B</td>
<td>July 18</td>
<td>420</td>
<td></td>
</tr>
<tr>
<td>203B</td>
<td>July 19</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>204B</td>
<td>July 20</td>
<td>2,640</td>
<td></td>
</tr>
<tr>
<td>205B</td>
<td>July 21</td>
<td>2,160</td>
<td></td>
</tr>
<tr>
<td>206B</td>
<td>July 22</td>
<td>2,580</td>
<td></td>
</tr>
<tr>
<td>209B</td>
<td>July 23</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>211B</td>
<td>July 24</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>212B</td>
<td>July 25</td>
<td>2,760</td>
<td></td>
</tr>
<tr>
<td>213B</td>
<td>July 26</td>
<td>2,040</td>
<td></td>
</tr>
<tr>
<td>214B</td>
<td>July 27</td>
<td>1,920</td>
<td></td>
</tr>
<tr>
<td>217B</td>
<td>July 28</td>
<td>540</td>
<td></td>
</tr>
<tr>
<td>218B</td>
<td>July 29</td>
<td>2,160</td>
<td></td>
</tr>
<tr>
<td>221B</td>
<td>July 30</td>
<td>2,640</td>
<td></td>
</tr>
<tr>
<td>223B</td>
<td>July 31</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>224B</td>
<td>Aug. 1</td>
<td>360</td>
<td></td>
</tr>
<tr>
<td>225B</td>
<td>Aug. 2</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>234B</td>
<td>Aug. 9</td>
<td>38</td>
<td></td>
</tr>
</tbody>
</table>

1 Averaged over 2-hour period.
hour or less). Areas of excessive stress are easily detected because of the relatively large percentage increase in the micro-seismic production (from tenfold to a thousandfold). Most secondary mining problems are included in this class. In the second class there is some preexisting evidence of excessive stress, such as cracking, recurrent spalling, or other visible indications of ground movement. For problems in this class the method is used to determine extent of the affected area, to estimate the magnitude of the stress, and to ascertain how these quantities change with time. Sometimes the method is used to study the cause of the disturbance and to predict if and when failure will occur. A wide variety of problems fall in this class; the rock-burst problem is a specific example.

In either type of investigation detecting and localizing stress areas and determining whether the stress is increasing or decreasing are relatively quantitative procedures. On the other hand, determining the magnitude of the stress, particularly in relation to failure if it occurs, and establishing a cause are qualitative procedures that involve a knowledge of the physical and the micro-seismic properties of the rock and an understanding (based on theoretical consideration) of the stress pattern that should exist in the type of structure under study. An example of each type of structural stability investigation follows.

INVESTIGATION IN CLIFFS-SHAFT IRON MINE

One of the most extensive investigations conducted to date was performed in the Cliffs-Shaft mine, The Cleveland-Cliffs Iron Co., Ishpeming, Mich. The objectives of the study were twofold: (1) To determine if the existing system of mining created a relatively stable system of openings, that is, one in which the pillar and side-wall stresses are low compared with the strength of the rock; and (2) to determine if some part of the pillar ore remaining in a mined area could be removed without appreciably affecting the stability of the stope.

This ore body comprises an interconnected series of irregular deposits, which lie within an east-west synclinorium. The deposits range in size from 100 to over 1,000 feet in length, 50 to several hundred feet in width, and 20 to 100 feet in height. Although the deposits are interconnected, they are usually sufficiently isolated that they may be considered structurally inde-

![Figure 6.—Plan of Test Stope in Iron Mine.](image-url)
pendent. The ore is a relatively strong, dense, specular hematite containing some random stringers of jasper (jaspilite). It averages 59 percent Fe, and the crushing strength averages 30,000 pounds per square inch (p. s. i.). The immediate hanging-wall rock varies from stope to stope but is usually one of three types: argillaceous slate (graywacke), jasper, or conglomerate. Several hundred feet of competent quartzite (Goodrich) overlies the ore body and forms the structural cover to the mine. A plan (normal to the dip of the ore body) of the stoping area selected for test is shown in fig 6.

This stope originally was mined in 1935 and before this investigation had remained open for 10 years without any significant roof falls or indications of structural instability, such as pillar cracking, hourglassing, or induced-fracture patterns. No mining was being done directly above or below this area. Although mining was in progress along the dip both above and below the stope, the area bounded by the broken lines in figure 6 is sufficiently isolated by the stope walls on the north and west and by the mass of pillars of lean ore on the south and east that it could be considered structurally independent. The average stope height was 25 feet, and the roof span between pillar and pillar or pillar and side wall (minimum distance) was 20 to 25 feet. The immediate hanging-wall rock, graywacke, forms a sharp contact with the ore. This rock is known to make a relatively poor roof. The cover (stope roof to surface) was 850 feet. The pillar area under investigation was roughly 150 by 200 feet or 32,500 square feet, of which 7,800 square feet was pillar support (minimum cross-sectional area through pillars). The percentage of mined area in the stope was 76.

Before this investigation was begun, the average pillar stress, \( S_e \), was approximately 4,900 p. s. i., calculated from the relationship (2, p. 10)\footnote{\( S_e = S_r \left( \frac{100}{100 - R} \right) \),}

where \( S_r \) is the rock stress before mining, or

\[ S_r = \frac{p^2 h}{12R} = \frac{200 \times 850}{144} = 1,180 \text{ p. s. i.}, \]

\( p = \text{rock density} = 200 \text{ lb./cu. ft.}, \]

\( h = \text{height of cover to surface, 850 ft.}, \]

\( R = \text{mined area} = 76 \text{ percent or percentage recovery}. \]

The pillar stress is about 16 percent of the crushing strength of the ore (average 30,000 p. s. i.).

**DESCRIPTION OF TESTS**

Before any secondary mining was begun in the area, the stability of the stope was checked with the micro-seismic equipment. According to general practice, geophone holes were drilled to a depth of 6 to 8 feet in the side walls and pillars and as close to the roof as practicable. Maximum stress concentration should occur at roof and side wall or roof and pillar contacts. Geophones were installed first in widely separated holes, such as holes 2 and 5, and the seismic conductivity of the rock was checked. It was found that a light hammer blow with a 1-pound hammer would travel 200 feet or more. This represents a relatively good conductivity, and in all subsequent tests the geophones were spaced at intervals not greater than 100 feet, that is, not more than 100 from its nearest companion. Geophones were then installed in holes 3, 4, 5, 6, 7, 9, 10, and 12, and recordings were made (during off-shift periods) for a period of 2 weeks. Geophones could not be used in holes 1 and 2 because the fly rock from blasting cut the geophone cables. The micro-seismic rate from each geophone averaged less than one per hour, and no coincident micro-seismisms (received simultaneously by two or more geophones) were recorded. The results indicated complete stability in the stope.

Pillar E was removed first. An 8-hole slabbng round, a 2-hole slabbng round, and a final 2-hole round to remove the remanent were fired within a 5-day period. Samples of the data following the firing of each of the rounds are given in tables 3, 4, and 5. As will be noted, these data are similar in that during the first 10 minutes following the firing of each round the micro-seismic rate from each of the geophone holes was extremely high (up to 6,000 micro-seismisms per hour), but after 2½ hours the rate had generally dropped from \( \frac{3}{4} \) to \( \frac{1}{4} \) of that immediately after firing. After 16 hours the micro-seismic rates from all geophone holes had dropped to less than 10 per hour, a value which was considered representative of stable ground. These data show that the rock in this stope is extremely sensitive to changes in stress; that is, the micro-seismic production with change of stress is high. As would be expected, the geophones closest to pillar E area produced the highest rates and the more distant geophones the lower rates. Virtually all of the micro-seismisms picked up by the more distant geophones (for example, in holes 5 and 6) were coincident with the micro-seismisms picked up by the geophones in pillar E area. Thus, it was concluded that the stress pattern in the roof was affected only in the vicinity of pillar E. The rapid decrease in the micro-seismic rate after blasting indicated a quick readjustment of stresses. The roof in this area was trimmed 24 hours after the pillar was removed. A small number of pieces weighing not more than 100 pounds were removed from the area where pillar E contacted the roof; no roof trimming was required thereafter.
Table 3.—Micro-seismic rate after blasting, pillar E, round 1, micro-seisms per hour

<table>
<thead>
<tr>
<th>Time after round</th>
<th>Geophone hole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>First 10 minutes</td>
<td>780</td>
</tr>
<tr>
<td>2½ hours (10-minute sample)</td>
<td>66</td>
</tr>
<tr>
<td>16 hours (4-hour sample)</td>
<td>7</td>
</tr>
</tbody>
</table>

1 Not recorded.

Table 4.—Micro-seismic rate after blasting, pillar E, round 2, micro-seisms per hour

<table>
<thead>
<tr>
<th>Time after round</th>
<th>Geophone hole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>First 10 minutes</td>
<td>1,800</td>
</tr>
<tr>
<td>2½ hours (10-minute sample)</td>
<td>192</td>
</tr>
<tr>
<td>16 hours (4-hour sample)</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 5.—Micro-seismic rate after blasting, pillar E, round 3, micro-seisms per hour

<table>
<thead>
<tr>
<th>Time after round</th>
<th>Geophone hole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>First 10 minutes</td>
<td>1,500</td>
</tr>
<tr>
<td>2½ hours (10-minute sample)</td>
<td>72</td>
</tr>
<tr>
<td>16 hours (4-hour sample)</td>
<td>7</td>
</tr>
</tbody>
</table>

Pillar A was removed next, and at the same time a slab was removed from pillar D. Pillar A was removed with four slabbing rounds, and the micro-seismic results were essentially identical with those obtained during the removal of pillar E, except that after firing the third round a high micro-seismic rate persisted from geophones 10 and 7. Examination of the area disclosed that a loose slab had developed in the roof. This was removed, and the micro-seismic rates from these geophones returned to less than 10 per hour. The removal of pillar A was continued without further difficulty. In the same manner pillar C was slabbed, pillar G was removed, pillars F and H were slabbed, and pillars J and K were removed. The micro-seismic data obtained during these operations were similar to those obtained during the removal of pillars E and A, except during the removal of pillar J. The behavior of the roof around pillar J appeared normal during the slabbing rounds. However, immediately after the removal of the final remnant, which was about 8 feet square, a large roof fall occurred. The slab was 2 or 3 feet thick and was estimated to weigh several hundred tons. Apparently, this slab was being supported by a small remnant without producing any excessive stress in the remnant, as there was no exceptionally large micro-seismic activity in this area. This is not inconsistent with experience, because if the complete weight of the slab had been supported by pillar J it would not have represented an increase in the stress of more than 100 p. s. i. The roof in the vicinity of pillar J remained noisy for several months following this fall, and roof-trimming operations in this area were not started until after this period. After the removal of pillar J, pillar K was removed without any difficulty, completing the program for this area.

These pillar-removal operations reduced the cross-sectional area of the pillars from 7,800 to 5,100 square feet. The mined area in the stope was increased from 76 to 84 percent, and the maximum stress in the pillar, calculated from equation 1, increased from 4,900 to 7,500 p. s. i. Correspondingly, the average pillar stress in-
increased from 16 to 25 percent of the compressive strength of the rock.

CONCLUSIONS

The investigation in this mine was carried out during a 2-year period, which permitted ample opportunity to study the effects produced by removing this support from the stope. The following conclusions were drawn from the investigation:

1. The rock in this mine is micro-seismically sensitive to small changes in stress. Partly detached slabs weighing no more than a few tons can be detected by this method.

2. The removal of pillars in the stope induced local stresses in the overlying roof, which re-adjusted, usually within 24 hours, and thereafter afforded safe working conditions. In no instance did the roof stresses induced by the removal of a pillar extend beyond the area surrounded by the neighboring pillars. In other words, the general stability of this stowing area was not significantly affected by the removal of this pillar ore. This fact not only indicated that a portion of the remaining pillar ore in the mine could be removed without danger of general subsidence but that in future mining the recovery could be increased from 75 to 85 percent without danger.

3. Before these pillar-removal operations the roof spans from pillar to pillar or pillar to side wall were 20 to 25 feet. After 5 pillars were removed, the roof spans ranged from 50 to 60 feet, a twofold to threefold increase. In four areas (created by the removal of pillars E, A, G, and K) no serious roof falls resulted from this increase in span. However, after pillar J was removed a substantial roof fall occurred. Apart from safety considerations, these roof falls are undesirable because either the ore must be selectively scraped from the stope or a serious dilution of the ore must be accepted. In retrospect, it was concluded that it would have been more desirable and operationally just as feasible to remove a portion of each pillar by slabbing rather than removing alternate pillars. This procedure could result in the same recovery of pillar ore from a stope without increasing the roof spans by more than 5.5 feet. Thus, the possibility of dilution from roof falls could be minimized. Also, in future mining, roof spans in this type of rock (graywacke, argillaceous slate) should not exceed 30 feet if dilution is to be avoided.

INVESTIGATION IN ZINC MINES WORKS

A structural stability investigation of the second type was made in the Zinc Mines Works, Tennessee Coal & Iron Division, United States Steel Corp., Jefferson City, Tenn., with the objective of ascertaining the magnitude, areal extent, and, if possible, the cause of stresses that were reported to be affecting the stability of a large stoping area. Geologically, the mineralization (sphalerite) occurs in the Kingsport dolomite 200 to 300 feet below the surface. The Mascot dolomite overlies the Kingsport dolomite to the surface. Both formations are in the Knox dolomite. In general, the rocks are thick-bedded, massive dolomites and recrystallized limestones. In places shaly partings separate the thick members and also are present within a few members. The area has been subject to a moderate amount of post ore faulting. However, the faults are all cemented to the extent that it is possible to diamond-drill through the fault zone without breaking the core. At no place in the mine is there any evidence of recent movement along fault planes.

A plan of the affected stoping area is shown in figure 7. The overall stope dimensions were approximately 250 by 310 feet. The area within the broken lines of figure 7 is 78,000 square feet. The maximum stope height was 115 feet and the cover to the surface 175 to 200 feet. The roof over the stope arched to the side walls; the pillars in the center of the stope were over 100 feet high and those near the side wall 30 to 60 feet high. Seventy-five percent of the area was mined. The average pillar was 1,100 square feet or approximately 33 feet square. The average and maximum roof spans were 33 and 40 feet, respectively. No mining was being done over or under this area, and the stope was sufficiently separated from other mining operations to be considered isolated in so far as stress is concerned.

Mining in this area was begun in 1942, and until March 1945 no general instability in the stope had been observed. However, some small areas of local stress had been noted; for example, in 24 S “spitting” rock, working ground, and difficulty in trimming the area free from loose rock had been reported.

In March 1945 the first of the two rock failures in this stope were reported. The first failure was accompanied by a loud, audible report. Only a small quantity of rock was dislodged; however, cracks appeared in the roof and nearby pillars. The second failure occurred in May 1945 and was intense enough to be classified as a rock burst. Shortly before the burst “working rock” was heard, and the miners left the stope. The burst was accompanied by a loud report and flying rock, and the vibration was felt at the shaft approximately 1,500 feet from the stope. The micro-seismic investigation in this stope was started approximately 2 months after this burst, and during this period there was no other visible evidence of ground movement.

For a cover of 200 feet, a rock density of 175
pounds per cubic foot, and a recovery of 75 percent the average pillar stress, calculated from equation 1, is 980 p. s. i. As the crushing strength of the ore is approximately 25,000 p. s. i., the average pillar load was less than 1/25 of the crushing strength. Moreover, the stress concentration at the pillar crown or other points of small curvature should not have exceeded the average pillar stress significantly. Hence, these rock failures should not have resulted from the creation of the underground opening.

DESCRIPTION OF TESTS

Since the cause of the pressure disturbance was unknown, a more extensive micro-seismic installation was employed. Twenty-three geophone holes were drilled in the stope roof (directly above pillars), side walls, and pillars, as shown in figure 7. Also, 2 geophone holes were drilled in a small stoping area designated as area 24 I approximately 450 feet to the south. Five micro-seismic recorders (10 geophones) were used throughout the test—4 in the stoping area and 1 in area 24 I.

Hammer-blow tests disclosed that the rock had a good seismic conductivity; hammer blows in area 24 I were picked up in the stope, a distance of 350 to 450 feet. A geophone-to-geophone separation of 100 feet was considered adequate for the study of the problem. How-
ever, for subsequent roof-control purposes, a spacing of 50 feet was employed.

The micro-seismic recorders were operated from 4:00 to 7:00 a.m. and p.m. each day. During the first 4 days of the test the micro-seismic rate from each geophone was very low, averaging about 5 micro-seisms per hour. On the fifth day mining was resumed in area 24 B. Also, apparently by coincidence, the ground began to work in 24 S. The micro-

From geophone hole 9 in 24 S jumped to about 350 per hour, of which over 100 per hour were noncoincident, showing a local disturbance in the area. The micro-seismic count from holes 1, 2, 3, 4, 5, 7, and 8 averaged 170 micro-seisms per hour, most of which were coincident, showing a disturbance outside the area. Mining was discontinued in 24 B, and on the following day the rate from geophone 9 dropped to 78 per hour; 72 originated in the 24 S area, indicating a continuation of the working ground in this area. The rate from all other geophones dropped to an average of 10 per hour, most of which were coincident, originating in 24 S.

These incidents indicated that the ground was micro-seismically sensitive.

The ground in 24 S continued to work sporadically throughout the year this project was in operation. There was considerable evidence of fresh loose rock, both on the roof and side walls. Several attempts were made to trim the area, but these only resulted in increased ground movement, usually to the point where audible working was heard. However, this movement in 24 S did not affect the rock stability in any other part of the stope; and, conversely, the stability in 24 S was not affected by local stress disturbances created in other parts of the area.

After a week of observation it was concluded that, with the exception of area 24 S, there was very little micro-seismic generation in this stope, indicating general stability.

Mining activity was resumed in the stope by slabbing some of the pillars and changing the stress pattern. Corresponding micro-seismic activity was noted. This operation was started by slabbing pillar K and was continued by removing a brow between pillars K and E and then slabbing pillar E. The micro-seismic results followed the pattern for stable ground; that is, the micro-seismic rate was high immediately after blasting and generally decreased rapidly (in 30 to 60 minutes) to a background rate of less than 10 micro-seisms per hour. Also, the micro-seismic production was usually from the approximate area of the blast; that is, the geophone closest to the blast picked up the largest micro-seismic production. The more distant geophones picked up a smaller number, most of which were of lower intensity and were coincident. If micro-seismic production continued for over an hour, it was always found to be associated with loose in the roof or on pillars; when the loose was removed the micro-seismic rate returned to the normal background level.

The test procedure was continued for over a year, with no significant difference in result. During this period 4 pillars were slabbed and 2 areas of roof (brows) removed. The two geophones placed in 24 I did not pick up any coincident micro-seisms (except blasting) from the large stope.

CONCLUSIONS

It was concluded that the stope was not under excessive stress. The cause of the rock failure and burst was undetermined. Three speculative causes were considered: (1) Both rock failures occurred in crystalline limestone members, which may have been under residual stress; (2) the limestone may have been affected by exposure to moisture, changes in temperature, or other weathering conditions; (3) the stress in the limestone may have been affected by the rate of mining. At the time of these failures the stope was being mined by five crews. After the failures the stope was never mined by more than one crew. Possibly, the higher rate of mining from five crews did not permit a normal readjustment of surface stresses.

When the micro-seismic tests were terminated, mining in the stope was continued. Additional pillars were slabbed and roof and side walls were recovered. In the area between pillars B, F, and E the roof was opened to an unsupported span of 65 by 90 feet. No bursts or other major failures were experienced.

ROCK-BURST STUDY

AHMEEK COPPER MINE

The generation of micro-seisms in rock under stress was first noted in 1939 in the Ahmeek mine, Calumet & Hecla Mining Co., Ahmeek, Mich. The occurrence of these noises suggested a means of predicting rock bursts, and micro-seismic studies were directed toward that objective (5, 6). These studies were made during 1939, 1940, and 1941 and again in 1951, 1952, and 1953.

The Ahmeek mine is in the Kearsage, Amygdaloid lode, of the Keweenawan copper-bearing series. The lode dips approximately 35° at the surface and decreases slightly with depth. The workable thickness at the lower levels ranges from 6 to 10 feet, and the maximum vertical depth of the mine is approximately 5,000 feet. The copper-bearing rock is either a gray or a brown-to-red amygdaloidal basalt varying in hardness and strength. The compressive
strength of the ore zone rock ranges from 17,000 to 50,000 p. s. i., with an average strength of 40,000 p. s. i. The micro-seismic characteristics of this rock, as determined in the laboratory, are that the first micro-seisims occur at 75 percent of the crushing strength and the rock shatters when broken (8).

The average stress (equation 1) on this rock at a depth of 4,000 feet before any mining was done was:

$$S_s = \frac{\rho h}{144} = \frac{168 \times 4,000}{144} = 4,700 \text{ p. s. i.,}$$

which is approximately one-eighth of the crushing strength. Thus, a stress multiplication factor of 8 resulting from mining should cause this rock to fail. The mining method employed is a retreating sublevel system of open stoping with regularly spaced pillars. Once the stopes are mined, most of these pillars crush and some caving of the back occurs. Thus, these regularly spaced pillars offer little or no support after the stope is mined, and most of the load of the overlying rock must be carried on the solid rock in the shaft pillars, on unmined remanents, or on broken rock in caved areas.

Because the support offered by the caved rock in the mined areas cannot be measured, it is impossible to calculate stresses on the remaining support in the mine. However, the stress in a rib-pillared area in an uncaved area can be estimated. Figure 8 is a detailed plan of a stoping area (about 1942) showing the small pillars left during the mining operation. The cross section of these pillars was approximately 6 by 14 feet. Somewhat larger pillars were left at the draw points and at the top where the stope connected to the level above. The stope width was 42 feet, and approximately 90 percent of the area was mined. The average stress on the pillars (equation 1) is

$$S_s = S_s \left( \frac{100}{100 - R} \right) = 4,700 \left( \frac{100}{100 - 90} \right) = 47,000 \text{ p. s. i.}$$

Thus, the average pillar stress is greater than the average pillar strength, and the pillars should crush as mining progresses on a given level. Also, the average stress on the unmined rock adjoining this pillar area must approach the average crushing strength of this rock.

By 1941 mining had progressed to the 45th level between Nos. 2 and 3 shafts and to the 39th and 40th levels to the left of No. 3 shaft and to the right of No. 2 shaft. (See fig. 9.) The main supports for the rock over this mined area were the Nos. 2 and 3 shaft pillars, unmined rock and ore below the 45th level, remanent pillars, 35th level, and the caved filled stopes. By 1951 mining had progressed to the 51st level to the left of No. 3 shaft and to the right, left, and beneath the No. 2 shaft. Thus, the No. 3 shaft pillar and the unmined ore to the right of this pillar were furnishing most of the support for the overlying rock at that time.

**INVESTIGATION OF 1941**

An extensive micro-seismic investigation was made in 1941 on the 43d level (vertical depth, approximately 4,000 feet). Several geophones were installed on the 43d level in an area that was particularly subject to bursts. The geophones were placed near the stoping areas on this level and, as the face advanced, were moved so that they were always approximately the same distance from the face. Recordings were made during the 4-hour idle period following each of the working shifts for a period of 40 days. A detailed analysis of the data indicated that the best criterion for predicting a burst was as follows: If the average number of recorded micro-seisims increased in any interval not exceeding 24 hours by a factor of 2 or more, a burst was indicated. Furthermore, if after

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**Figure 8.—Stope Plan of Ahmeek Mine.**
such an increase the number of micro-seisms continued to increase, the possibility of a burst was presumed to persist. On the basis of this criterion, 14 burst predictions would have been made during the 40-day period; 9 would have been followed by rock bursts within 12 hours or less, 5 would not have been followed by bursts, and 2 bursts would have been unpredicted (both of which occurred on the same day). The micro-seismic method, as employed in this test, was not considered accurate enough for routine prediction purposes.

INVESTIGATION OF 1951–53

A second investigation was conducted in the same mine between May 1951 and November 1953. Micro-seismic equipment was installed on the 45th level (approximately 160 feet vertically deeper than in the earlier test), and geophones were placed over the working stopes on the 46th level in the same manner as in the previous tests. During this 10-year interval between these investigations the rock-burst condition had worsened considerably in this part of the mine; 3 to 10 bursts per day were occurring in active and nearby worked-out stopes in the area of the 46th level. A significant difference between the micro-seismic behavior of this stoping area and that tested in 1939–40 was also immediately noted. The average micro-seismic rate was considerably higher than in the previous test, even at points some distance from the working stopes, where formerly the rate was nearly zero. Hence, the ratio of the average to peak micro-seismic rate was much smaller than in the 1941 tests. These results indicated that the 45th level area was under a relatively high stress and that the differences between the average stress and that necessary to cause bursts would be relatively small. Therefore, in comparison with the previous test, it was improbable that any improvement or even as good results could be obtained, so this approach to the problem was discontinued.

However, the investigation was continued in an effort to find another approach to the problem—if rock bursts could not be predicted, it might be possible to make changes in mining methods that would reduce their frequency or severity or induce them to occur at a time when the stopes were not operating. The micro-seismic equipment was employed on a 24-hour-per-day basis to record the time and occurrence of all bursts, so that rock-burst rate vs. mining-change studies could be made. The type of micro-seismic equipment employed in the 1940 and the first phase of the 1951 tests was not satisfactory for this type of recording because of its high sensitivity to drilling and other man-made disturbances. An equipment of reduced sensitivity (about three-hundred-fold) was developed which could be employed close to operating stopes. The equipment would record rock bursts and large-scale crushing and blasting but no other type of disturbance.

Two changes in mining were effected: (1) The stope widths were reduced from 42 to 25 feet, and (2) electric standard delay caps were substituted for fuse firing. The latter change was made in an effort to create a large bump at the end of a shift and thereby trigger bursts in the following off-shift period, a procedure which has been employed successfully in another rock-burst mine. Unfortunately, owing to the urgency for reducing the rock-burst hazard, these two changes were made simultaneously, thereby complicating the analysis of results.

A substantial reduction was made in the occurrence of bursts in the working stope, as noted by the miners, ground bosses, and supervisory staff. The data showed that the number of bursts in off-shift periods, that is, in the period immediately following the end of the shift, was increased by as much as 40 percent, with a corresponding reduction in bursts during on-shift periods.
BIBLIOGRAPHY


