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INVESTIGATION OF ELECTROMAGNETIC EMISSIONS IN A DEEP UNDERGROUND MINE

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ABSTRACT

Highly stressed rock in stopes continues to be a primary safety risk for miners in underground mines because it can result in failures of ground that lead to both injuries and death. Spokane Research Laboratory personnel investigated electromagnetic (EM) emissions in a deep underground mine in an effort to determine if these emissions could be used as indicators of impending catastrophic ground failure. Results suggest that (1) there is no increase in the number of EM emissions prior to recorded seismic activity, (2) some EM signals are generated during blasting, (3) interference from mine electrical sources mask seismic-generated EM signals, (4) EM emissions do not give enough warning (compared to seismic monitoring) to permit miners to leave a stope, (5) the distance an EM signal can travel in the rock is between 17.7 and 39.6 m (58 and 130 ft), and (6) current data acquisition systems do not differentiate between EM signals generated from seismic activity and random mine electrical noise. These results preclude monitoring EM emissions as precursors of impending catastrophic ground failure.

INTRODUCTION

Personnel from the Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health (NIOSH) conducted field studies to collect electromagnetic (EM) emissions at the Galena Mine, Wallace, ID (figure 1). The goal of the research was to determine if EM emissions were valid precursors to imminent ground failure. Identifying such an association could be useful as an indicator of potential rock failure in underground mines.

Acoustic and EM emissions coincide when certain types of rock, especially quartz and quartzite (Nesbitt and Austin, 1988), break. Because EM emissions travel at the speed of light and acoustic emissions travel at the speed of sound, theoretically EM emissions could be a precursor to seismic activity (i.e., ground failure, rock bursts).

Acoustic (including microseismic and seismic) monitor-ing of a rock mass to detect ground movement in deep underground mines has been done successfully for several years. Various earthquake researchers have noted that occasionally the number of EM emissions would increase prior to a large earthquake. EM emissions have been proven to be associated with rock failure in controlled laboratory research; however, to date, EM emissions have not been used successfully to detect imminent ground failure in deep underground mines.

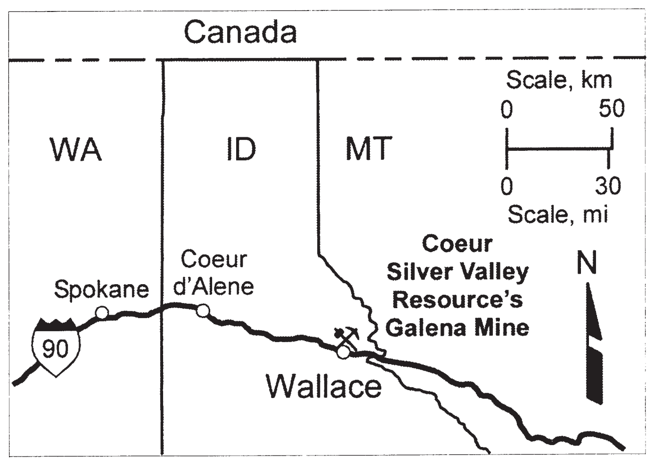

Figure 1.—Location of Galena Mine, Wallace, ID.

PREVIOUS STUDIES

Light emissions and low-frequency electrical phenomena associated with seismicity in underground mines and earthquakes have been reported for hundreds of years (Brady and Rowell, 1986). Most of this work involved the identification of EM emissions as an indicator of earthquakes. EM frequencies in both earthquakes and laboratory tests range from 0.01 Hz to 30 MHz.

EM Source Mechanisms

- Brady and Rowell (1986) summarized four mechanisms that cause light to be emitted from fracturing rock: (1) rock fragments frictionally heated to incandescence, (2) electrostatic discharge produced by the deformation of piezoelectric minerals or charge separation on fractured surfaces, (3) plasmas produced by rapid and intense heating of rock material, and (4) excitation of the ambient atmosphere by particle (electrons or positive or negative ions) bombardment. Brady and Rowell conclud-ed that the light emitted from test rocks in the laboratory was caused by excitation of the ambient atmosphere by particle bombardment.

- Zi-qiang and others (1988) examined three sources of light: (1) heat radiation from friction, (2) electrostatic discharges produced by piezoelectric effects or charge separation on fractured surfaces, and (3) excitation of the ambient atmosphere by particle bombardment. Because light emissions were observed only at the moment when electrons struck air molecules, the authors concluded that the most likely source of EM emissions was excitation of the ambient atmosphere by particle bombardment.

- Brady (1996) detected electrical signals in the frequency band of 900 to 5,000 Hz using both coil and monopole antennas. EM emissions coincided with the final failure of an unconfined rock sample. Brady then concluded that the low-frequency signals (900 to 5,000 Hz) recorded after rock failure were caused by the rotation and vibration of charged rock fragments. His observation was consistent with the hypothesis that no low-frequency EM emissions should occur if fracturing was confined (thus making particle motion impossible). He noted that no emissions were evident at frequencies greater than 10 kHz and that emissions were evident only in the near field and not the far field.

Earthquakes

Martner and Sparks (1959) noted electrical potential prior to the arrival of seismic waves at the surface of the ground. About 30 minutes prior to the arrival of main earthquake shocks, Gokhberg and Morgounov (1982) recorded EM emissions at frequencies of 27, 81, and 1.5 kHz and 1.63 MHz. Later, Migunov and others (1984) documented EM emissions in the frequency range of 0.5 to 50 kHz that were associated with seismicity from earthquakes. Fujinawa and Takahashi (1990) observed EM emissions in the 0.01- to 12-Hz and 1- to 9-kHz frequency bands hours before earthquake activity in Ito, Japan. Fujinawa and Kumagai (1992) observed ultralow-frequency (0.01 to 0.6 Hz) to very low-frequency (1 to 3 kHz) electrical emissions before, during, and after volcanic eruptions.

Laboratory Tests

- Tuck and others (1976) tested a cube of quartzite coupled with a quartz crystal to determine piezoelectric emissions when a 0.5-kg (1.1-lb) hammer was used as a seismic source. They concluded that no piezoelectric fabric was found; therefore it would be difficult to use EM emissions for the exploration of ore bodies.

- Nitsan (1977) fractured quartz crystals, tourmaline crystals, and quartz-bearing rocks and recorded EM emissions in the frequency range of 1 to 10 MHz. His interpretation of the source of the emissions was piezoelectricity.

- Goncharov and others (1980) tested several large (0.55 by 0.55 by 0.65 m [19.4 by 19.4 by 22.9 ft]) blocks of concrete containing pieces of granite by applying load and record-ing both EM and acoustic emissions as the concrete failed. They recognized the fundamental problem of simultaneously recording both EM and seismic emissions and concluded that the number of EM emissions decreased as their amplitude increased. They also found that the ratio of EM to acoustic emissions post-fracturing was 20:1. Prior to fracturing (initial loading), the ratio had been 7:1.

- In 1981, Bishop studied piezoelectric effects in quartz-rich rocks. Using a laboratory-designed system, he attempted to prove that the axis of the quartz crystals was a factor in EM emissions. He found that a relationship existed between EM emissions and predictions of the c-axis orientation in quartz crystals.

- Hanson and Rowell (1982) tested quartzite from the Galena Mine, Wallace, ID. EM emissions peaked sharply below 40 kHz on three antennas, leading them to conclude that (1) fracture formation coincided with EM emissions, (2) EM emissions fell into a frequency range of less than 40 kHz, (3) EM emissions seemed to be directional, and (4) the amplitude of EM emissions seemed independent of stress, but not independent of stress drop.

- Khatiashvili (1984) showed that as the size of fractured crystals increased, electrical potential also increased.

- Ogawa and others (1985) used ball antennas covering the frequency range of 10 Hz to 100 kHz to measure EM emissions from crustal rocks broken in the laboratory. They found that sedimentary rocks containing less silica emitted less electromagnetism and concluded that the source mechanism for EM emissions was either contact or separating electrification and piezoelectrification.

- Zi-qiang and others (1988) fractured granite in the laboratory and found that the most intensive light pulse and acoustic emissions were recorded simultaneously at the moment of rock fracture.

- Yamada and others (1989) also fractured granite in the laboratory and recorded EM emissions in the frequency range of 80 kHz to 1.2 MHz. They concluded that, based on their work, the source of EM emissions was not a piezoelectric effect, but was related to new surfaces created by cracks.

- Weimin and others (1991) fractured quartz, limestone, and granite samples and reported that recorded EM emissions were a result of rock fractures.

- Rabinovitch and others (1995) tested granite and recorded EM emissions in the 100-kHz range. They also documented EM frequencies of as much as 10 MHz in quartz porphyry. Two types of EM pulses were noted, “short” pulses of 1-3 microseconds and “lengthy” pulses of more than 400 microseconds.

Theoretical Work

- Rabinovitch and others (2000) attempted to explain the mechanism for EM emissions and concluded that following early pore closure, microcracking and possibly coalescence occurred, while just before peak stress was reached, the rock collapsed. A summary of information about the frequency and wavelength of EM emissions showed that their frequency range was 1 kHz (with a wavelength of 300 km [186 mi]) to 10 MHz (with a wavelength of 30 m [98 ft]).

- Goldbaum and others (2001) identified four distinct EM emissions waveforms: short single pulses, a short chain of single pulses, an extended chain of pulses, and a new group, pulses along baseline voltage changes. Significant to their work were EM frequencies reaching 25 MHz (formerly believed to be only up to 10 MHz).

- Rabinovitch and others (2001) continued investigating mechanisms for EM emissions and concluded that the mechanisms for earthquake EM emissions were the same as for microfracturing in laboratory tests. They studied the Gutenburg-Richter type and Benioff strain-release relationship for earthquakes and found the relationship extended to the microlevel.

Underground

- Sobolev and others (1984) tested the value of collecting EM emission data as a method of prospecting for quartz veins and base-metal sulfides. They detonated explosive charges and measured the EM emissions generated by the excited minerals. Their tests showed EM signals generated by quartz veins at the Giant Yellowknife Mine (Canada) were in the range of about 8 kHz, which was similar to emissions from quartz broken in the laboratory. Further tests in a sulfide vein at the Sullivan Mine (Canada) also produced EM emissions as high as 350 kHz. Their conclusions were that quartz and sulfides such as galena, sphalerite, and pyrrhotite emit EM waves along their grain boundaries.

- Nesbitt and Austin (1988) recorded seismic and EM emissions at a depth of 2.5 km in an underground mine. They found that EM emissions preceded the seismic wave.

- O'Keefe and Thiel (1991) recorded EM emissions associated with blasting in rock quarries in Australia and recorded signals in the 20-Hz to 20-kHz range.

- Russell and Barker (1991) investigated expected EM emission amplitudes in exploration and found that the identification of true piezoelectric responses was difficult because their data acquisition system recorded both acoustic and piezoelectric signals as part of the same waveform. At best, they presumed that a portion of the signal collected was piezoelectric.

- Butler and others (1994) successfully mapped stratigraphic boundaries using emissions responses. They found they could map a boundary between glacial till and organic-rich fill by collecting emissions waveforms generated by either a sledgehammer or blasting caps as a seismic source. Their work showed that it was the boundary or interface of the glacial till and the organic-rich fill that was responsible for the emissions conversion and not the water table.

- Wolfe and others (1996) used emissions studies in an attempt to identify the depth of the water table. Using seismic refraction surveys and dc resistivity surveys in two drill holes as a baseline, they showed a consistent depth to the water table as compared to the baseline data. Thus their study demonstrated that emissions data could be acquired in an outwash plain.

- Russell and others (1997) used emissions techniques to identify quartz and sulfide veins in three underground mines. They were successful in identifying quartz veins, sulfide veins, and the boundaries between formations with differing permeabilities using data from EM emissions.

- Frid (1997b) concluded that EM emissions in coal mines lay in a narrow band from 30 to 150 kHz. He used 100 kHz as the most convenient frequency while examining EM emissions (1997a). He also concluded that the higher stress associated with rock near mine workings increased natural EM emissions.

- Frid (1999) used EM emissions to delineate stress in coal seams. He measured EM activity during borehole drilling and found that a hole nearing a stress peak excited a sharp increase in EM activity.

- Frid and others (2000) continued their work in the laboratory and attempted to correlate EM emissions with crack dimensions. They found that the amplitudes of EM emissions and their changes with loading were independent of both tensile and shear failure and that they were dependent only on the area of the entire crack.

- Frid (2001) recognized the value of using EM emission criteria to forecast rock burst hazards in coal mines by using the limiting value of broken coal volume, mine working width, coal seam thickness, and coal elastic properties.

- Sines and Knoll (unpublished oral conversation, 2000) used a data acquisition system to collect both seismic and EM emissions on the 4600 level of the Galena Mine. They sampled at a rate of about 7,200 samples per second (a Nyquist frequency of 3,500 Hz) using two monopole antennas 12.5 and 15.2 m (41 and 49.9 ft) long. They used no filters to eliminate low-frequency emissions and found numerous triggers on the EM antenna, which were initially thought to be coincident with seismic activity. However, when the EM and seismic waveforms were analyzed, they found that most of the seismic emissions had actually preceded the EM emissions, which is physically impossible. Further evaluation of the collected waveforms showed that most of the EM emissions were caused by mine cultural noise, which included the opening and closing of air doors (60-Hz solenoid), locomotive activity, and chute loading.

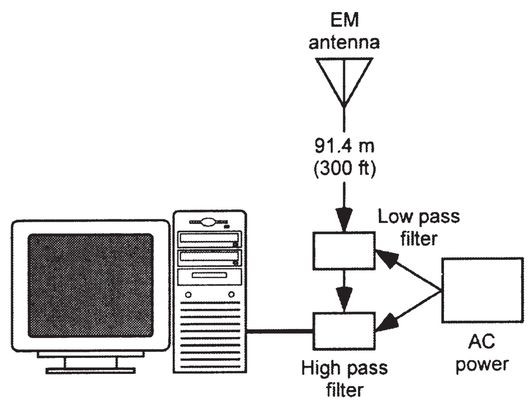

Figure 2.—Schematic of data acquisition system.

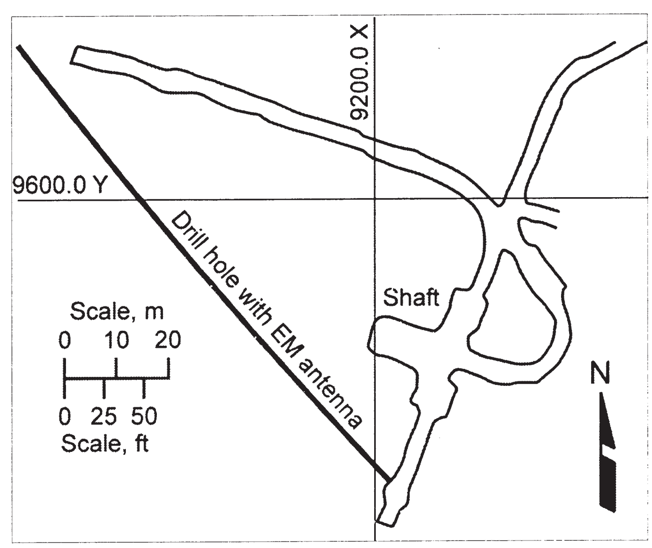

Figure 3.—Plan view of downhole antenna.

- Butler and others (2001) conducted field studies at the Brunswick No. 12 Mine in Canada in an attempt to link EM emissions with seismic activity and also to delineate sulfide ore. They used various antennas covering a range of frequencies from 1 Hz to 4.5 MHz. They found that broadband EM emissions with frequencies up to 800 kHz could be induced by seismicity and blasting. However, results did not confirm that EM emissions preceded seismicity.

- Vozoff (2002) attempted to demonstrate the use of EM monitoring as a warning system for roof failure in a large coal seam in Australia. He collected three complete data sets and concluded that of the three, one set coincided with a roof fall and was correlated with EM activity, one set might have had a "weak correlation at best," and one set had no EM correlations with roof falls.

TECHNICAL APPROACH

As noted above, many researchers have attempted to capture EM emissions before, during, or after ground failure (i.e., rock bursts) in underground mines. However, to date, none have conclusively linked rock breaking underground with EM emissions. The following work describes the methods and results of a study at the Galena Mine, Wallace, ID. It builds on the work of previous researchers, but uses new methods in an attempt to capture EM emissions from either blasting or rock bursting.

The equipment used included an ESG data acquisition system, ULTRAQ,[1] capable of sampling up to 10 million samples per second (Nyquist frequency of 5 million samples per second) on four channels and a Pentium 166 computer. The system was enclosed in a box to keep it as clean and dry as possible; fans were installed to keep air moving in the box. Voltages for triggering the system could be set as low as 1 mV. Figure 2 shows the setup for data acquisition.

Two monopole antennas constructed of solid copper wire and enclosed in plastic pipe sealed at both ends were used to collect EM emissions data. The first, 91 m (300 ft) long and having a resonance frequency of 821 kHz, was inserted into a drill hole extending from the 5500 level down toward an active stope (figure 3). The second, 3.8 m (12.5 ft) long and having a resonance frequency of 19,737 kHz, was suspended from the back above the data acquisition system about 91 m (300 ft) from an active stope.

Based on the work by Hanson and Rowell (1982), the ideal antenna length for EM data collection (considering EM frequencies of about 107 kHz) would be about 700 m (2,297 ft), which compared closely with EM frequencies (100 kHz) obtained in laboratory experiments from breaking rock. A "wound" antenna was also developed in the laboratory; however, this antenna failed to pick up EM waveforms.

[1] Mention of specific manufacturers or products does not imply endorsement by the National Institute for Occupational Safety and Health.

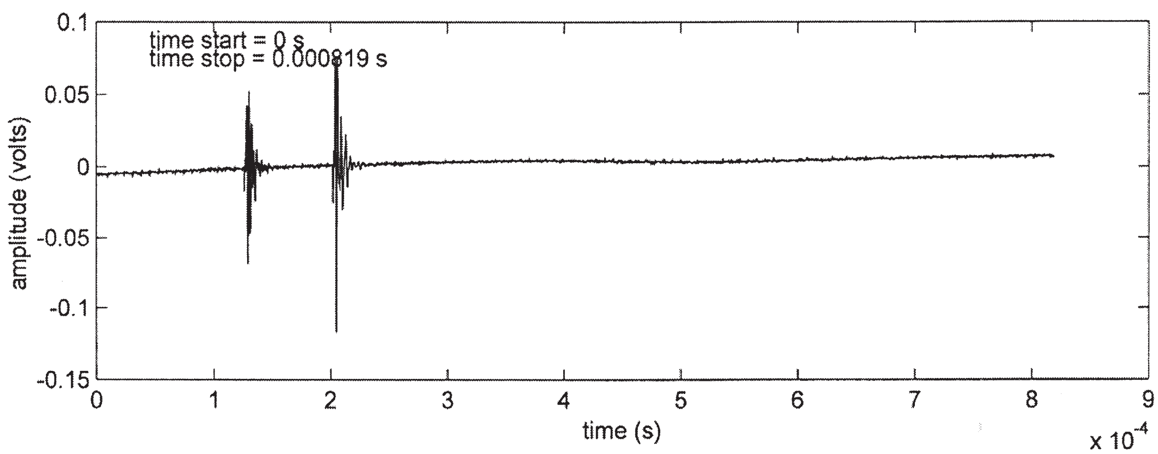

Figure 4.—Air door (electrical noise) waveform.

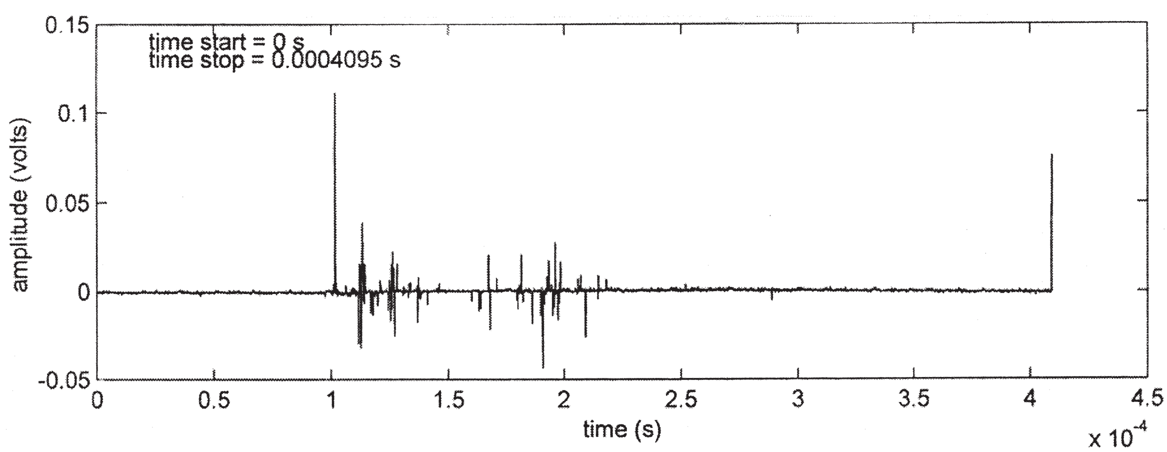

Figure 5.—EM emissions from striker.

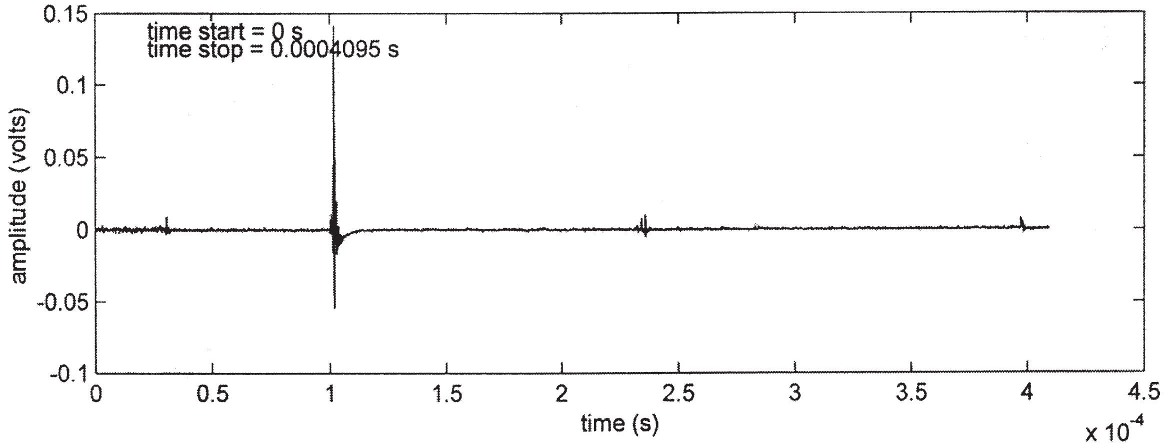

Figure 6.—EM event recorded during blasting.

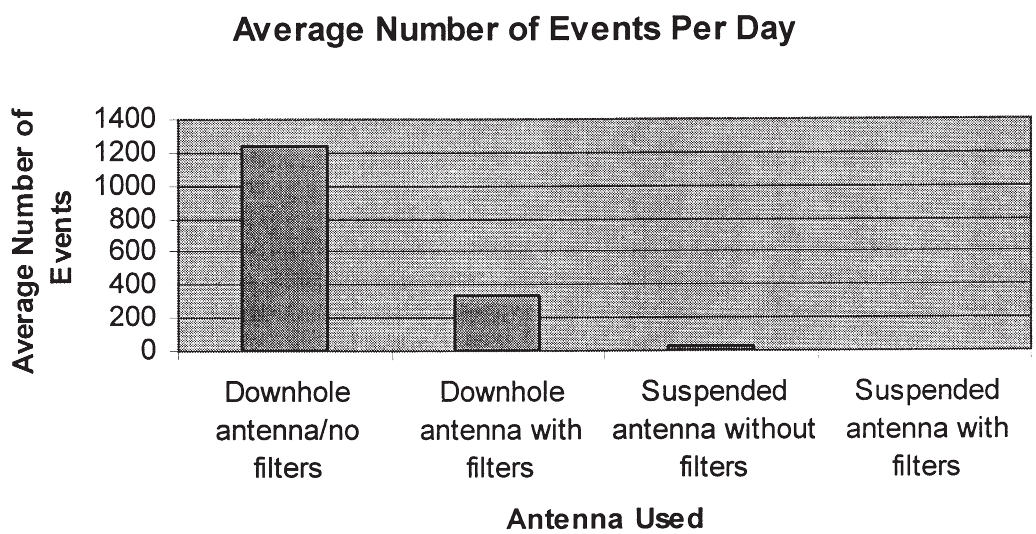

Figure 7.—Average number of events per day.

Initially, filters were not installed; however, both high-pass (2.56 kHz) and low-pass (102.4 kHz) filters were used after the first tests to trap a "range" of frequencies and eliminate any triggers that might be related to common electrical interference in the mine in the 60- to 120-Hz range. After several data sets were collected, use of the low-pass filter was discontinued, and only waveforms with frequencies above 2.56 kHz were collected and analyzed.

Table 1.—Attenuation of EM emissions (resistivity of the rock at 125 ohm/m).

Frequency (kHz)	Skin depth (m)	Skin depth (ft)	Attenuation (% of energy left)
5	79.1	259.4	64.2
10	55.9	183	53.5
20	39.5	130	41.3
40	27.9	92	28.6
80	19.8	65	17
160	13.9	45.9	8.2
320	9.8	32.4	2.9
640	6.9	22.9	0.7
1280 (1.28 MHz)	4.9	16.2	0.08
2560 (2.56 MHz)	3.5	11.5	0

In an effort to eliminate "grounding" problems in the mine stemming from the mine's ac power source, an independent dc power source was tried. However, the "noise" generated by the dc power source was too intense and automatically triggered the system. Therefore, the mine's ac power was used to operate the data acquisition system.

EM emissions decay at a rapid rate in rock (table 1), so attenuation was also a concern. As frequency increases, the distance the waveform can travel from the EM source to the antenna decreases. Therefore, if the frequency of an EM emission is high (2.56 MHz), the distance from the antenna to the EM emission source would be 3.5 m (11.5 ft), with virtually no energy left. However, if the EM emissions were at a much lower frequency (500 Hz), the distance between the antenna and an emission source would have to be nearly 79 m (260 ft), with about 64% of the energy left.

Different settings were configured in an attempt to record EM emissions. The EM source was a striker commonly used for igniting barbecue grills. The striker gives off a short EM emission.

RESULTS

Waveform identification

Figures 4 and 5 show waveforms collected with the system. Figure 4 is a waveform collected from the air door solenoid (60 Hz), and figure 5 shows an EM waveform where the striker was used as a source. The two waveforms are distinctly different. The EM waveform has a high-amplitude spike followed by smaller spikes originating from the striker. The air door waveform has a large spike that is followed by closely spaced decaying spikes. The air door waveform (and all electrical noise and grounding effects) is always characterized by four to five closely spaced spikes following an initial spike.

Downhole antenna without filters

Several different voltages, ranging from 10 mV to as much as 1 V, were tested as triggers; 50 mV was selected as the final triggering threshold at a sampling rate of 1 MHz. Data were collected for 5 days. The number of events triggered ranged from 900 per 24-hour period to as many as 1,589 per 24-hour period, with an average of 1,236. All the events were identified as electrical mine noise; no EM activity occurred during blasting.

Downhole antenna with filters

Test voltages ranged from 10 mV to 1 V. All voltages from 400 mV or less automatically triggered the data acquisition system; therefore, the trigger threshold was set at 400 mV at a sampling rate of 1 MHz. Data were collected for 21 days. The number of events recorded per 24-hour period decreased when the filters were in place and ranged from 281 per 24-hour period to as many as 581 per 24-hour period, with the average being 332 events per day. As with the unfiltered antenna, the events collected were identified as electrical mine noise, and no EM activity was recorded during blasting.

Suspended antenna without filters

We concluded that mine electrical grounding in the rock created voltage readings up to 1 V that were not EM related. We then tried a second approach, which was to suspend an antenna from the back where the antenna could not be grounded.

Trigger voltages ranging from 10 to 30 mV were tested at a sampling rate of 3 MHz and a trigger threshold of 30 mV. Data were collected for 5 days. The number of events ranged from two per 24-hour period to as many as 24 per 24-hour period, with a total number of 52 and an average number of 10 events per 24-hour period. As before, these events were identified as electrical mine noise.

System settings were then changed to a sampling rate of 4 MHz and a trigger threshold of 25 mV. Seventy-three events ranging from one per 24-hour period to as many as 43 per 24-hour period were recorded over a 9-day period, with an average number of eight events recorded per 24-hour period. These events again were classified as electrical noise.

Using a sampling rate of 10 MHz and a trigger threshold of 25 mV, the system recorded 107 events. Over a 7-day period, the number ranged from two per 24-hour period to as many as 24 per 24-hour period, with an average per day of 15. Again, waveforms collected were classified as electrical noise. No EM activity occurred during blasting. However, the result was a marked decrease in the amount of mine electrical noise recorded by the data acquisition system compared to the 24-hour period of sampling (with or without filters) in the downhole.

Suspended antenna with filters

Using information from work by Hanson and Rowell (1982), we installed a high-pass (2.56 kHz) filter that allowed EM waveforms with frequencies above 2.56 kHz to be collected. EM emissions were recorded for 17 days at a sampling rate of 10 MHz and a 25-mV trigger threshold. Twenty-eight waveforms were collected, of which nine occurred during blasting (figure 6). This was important because only waveforms associated with blasting were possibly associated with seismicity or rock breaking. Figure 7 summarizes the number of events collected using different methods.

CONCLUSIONS

Cultural noise associated with EM emissions in a deep underground mine can be caused by, but is not limited to, blasting, drilling, motors, air doors, ventilation fans, shaft noise, chute activity, power tools, welding, power surges, various types of power tools, and water pumps. Seismic activity can also be a source of EM emissions. A grounding effect caused by the mine's power source creates as much as 1 V of electrical interference in the mine rock. The effect of the interference on an antenna installed in a drill hole was enough to trigger the data acqusition system; therefore, nearly all mine electrical noise was recorded and mixed with possible "true" seismic-generated EM emissions. Various trigger voltages and the use and nonuse of the low-pass and high-pass filters provided a wide range of data. The best EM data came from the suspended antenna using a high-pass filter.

However, results to date suggest that (1) there is no increase in the number of EM emissions prior to recorded seismic activity, (2) some EM signals are generated during blasting, (3) interference from mine electrical sources mask true EM signals, (4) EM emissions do not give enough warning (compared to seismic monitoring) to permit miners to leave a stope, (5) the distance an EM signal can travel in the rock is between 18 and 40 m (58 and 130 ft), and (6) current data acquisition systems do not differentiate between EM signals generated from seismic activity and random mine electrical noise. In summary, these results preclude monitoring EM emissions as precursors of impending catastrophic ground failure.

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