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Relationship between radiated seismic energy and explosive pressure for controlled methane and coal dust explosions in an underground mine

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ABSTRACT

Examination of seismic records during the time interval of the Sago Mine disaster in 2006 revealed a small amplitude signal possibly associated with an event in the mine. Although the epicenter of the signature was located in the vicinity where the explosion occurred, it could not be unequivocally attributed to the explosion. A greater understanding about the seismicity from mine explosions is required in order to properly interpret critical seismic information. A seismic monitoring system located at NIOSH's Lake Lynn Experimental Mine has monitored 16 experimental methane and coal dust-based explosions. This paper describes the research conducted to quantify a relationship between measured values of radiated seismic energy and peak explosive pressure generated. The radiated seismic energy takes into account seismic signature characteristics such as the frequency content, amplitude, and duration. On the other hand, the size of the explosion is a function of the experimental design, dependent on factors such as the presence of an explosion-containment structure, the mine geometry, and the amount of initial explosive fuel used during the explosion. The seismic signatures from methane and coal dust explosions were analyzed using standard waveform analysis procedures. The procedures used to estimate the radiated seismic energy were conducted using self-produced programs, which are explained in this paper. The radiated seismic energy estimates were considered to be relative values for each experiment. A relationship was derived to correlate the relative radiated seismic energy to the size of the explosion, defined as the peak pressure generated. It was also observed during this study that an explosion-containment structure can act as a major seismic source. Recommendations are made, based upon the findings of this study, for improved collection of seismic data in the future.

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1. Introduction

1.1. Statement of the problem

Seismic monitoring provides a powerful means for detection and evaluation of events resulting from mining activity. Seismic monitoring assessments in the mining community can be made from a seismic network installed locally at the mine or records obtained from stations devoted to earthquake studies which are continuously recording, such as the US Geological Survey stations. Seismic signature characteristics such as arrival times, amplitudes, duration, and frequency content can help indicate the nature and location of the source. In the past, most mining-related seismic assessments have focused on events such as production blasts from quarries, roof falls, and rock fractures (Iannacchione et al., 2005a,b; Swanson et al., 2002). However, little or no effort has been put towards examining the characteristics of a signature emanating from a methane and coal dust explosion in an underground mine.

The Sago Mine disaster was a coal mine explosion that occurred in 2006 in Sago, West Virginia (Gates et al., 2007). During the time interval of the Sago Mine disaster, a small amplitude signal was identified on records of the closest regional seismic network stations (Chapman, 2006). The epicentral location of the small amplitude signal was at the Sago Mine. However, it was unclear whether the signature represented the explosion itself or another type of mining-related seismicity such as a large roof fall. This disaster provides an example of why these particular signatures should be researched. This paper presents a portion of the findings from a study aimed at examining seismicity from methane and coal dust explosions, with potential applications to forensic studies of mine explosions such as the Sago Mine disaster.

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1.2. Proposed solution and objective

The Lake Lynn Experimental Mine (LLEM) is a facility associated with the National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research. The research facility has conducted controlled methane and coal dust explosions since 1983. These experiments provide insight into the behavior and prevention of underground mine explosions (Cashdollar et al., 2006; Sapko et al., 2000). This facility provided an ideal location and opportunity to monitor the seismicity from controlled explosions in an underground mine. A seismic monitoring system was installed at the Lake Lynn Experimental Mine to collect seismic signatures emanating from methane and coal dust explosions. The objective of the study was to analyze seismic signatures collected by the seismic monitoring system to begin to understand their characteristics at different distances away from the source. For this paper, the relationship between the size of the explosion and the amount of seismic energy estimated from the explosion is examined. Prior to estimating the energy of the explosion, the seismic monitoring system was calibrated. The purpose of the calibration is to determine specific constants that were unknown at the time and were needed for the energy estimation. The results from the calibrations lead to the development of a spreadsheet which served as the program to calculate the seismic energy from the data.

Throughout the world there are a great number of seismic monitoring stations that have the ability to capture the characteristic ground vibrations caused by methane and coal dust explosions, however finding them in seismic records is very difficult if the time of the event is unknown. Analysis of these types of seismic records could not be found in other literature, and results provided in this study are hoped to take a first step in understanding these events when captured in the far-field. The accessibility of the Lake Lynn Experimental Mine allowed for the unique opportunity to monitor methane and coal dust explosions in an underground environment; however, the control of the experimental designs was not made available. The presence of explosion-containment structures and the amount of initial methane and coal dust to fuel the explosion used during the experiments were based on research needs related to mine seal design and was not controlled for the purposes of the study. Ideally, experiments with replicated designs would be monitored; however, since the facility was occupied with many other research projects at the time of the study, having the experimental setups adjusted specifically for this study was not possible. Thus, this study was considered to be an exploratory project where any finding or observation made from the seismic signatures would be considered beneficial.

2. Materials and methods

2.1. Lake Lynn Experimental Mine and instrument locations

The Lake Lynn Experimental Mine is a full-scale, underground mining research facility on the site of a former limestone quarry and underground mine. The facility is located approximately 96 km (60 miles) southeast of Pittsburgh, Pennsylvania, and 16 km (10 miles) northeast of Morgantown, West Virginia. The west side of the facility, known as the old workings, was mined when limestone was produced commercially from the site. This area of the research facility resembles a layout typical of an underground stone mine. The dimensions of entries in the old workings are 15.2 m (50 ft) wide by 9.1 m (30 ft) high. The east side of the facility contains mine drifts that are dimensioned to match configurations found in coal mines. The dimensions of these entries are 6.1 m (20 ft) wide by 2.0 m (6.5 ft) high. The size of the pillars in the simulated longwall gate roads is 24×12 m (80×40 ft). A-, B-, C- and D-Drifts are approximately 480–495 m (1575–1630 ft) long. E-Drift, which connects the entries at the inby end, is 155 m (510 ft) long. Instrument rooms in the mine are located approximately three-quarters of the way down C- and D-Drifts. These rooms are protected from the entry via blast-proof doors. The mine layout, including both uniaxial and triaxial geophone locations used for this experiment, is shown in Fig. 1.

The methane and coal dust explosions conducted at the Lake Lynn Experimental Mine were ignited at the face of either A- or C-Drift. The ignition chambers are highlighted in Fig. 1. The chosen locations of the geophones were distributed in the mine around the explosion test area at various distances. Over the time interval of the experiment, nine triaxial and three uniaxial geophones were utilized. Geophone 7 is not listed on the mine map because it is a "dummy" geophone used for testing purposes. Not all geophones were present for each test monitored at LLEM. The geophone placement was proactive as the study progressed—i.e., additional geophones were added to the existing array in specific locations as a response to new findings in the data. In some cases geophones had to be removed due to their locations interfering with other experiments at LLEM.

Geologically, the mine is located in the Greenbrier limestone formation (Triebsch and Sapko, 1990). A borehole drilled into the roof approximately 9.1 m (30 ft) high in the old workings of the mine showed the different formations at the test site. The borehole data were obtained from NIOSH engineers who conducted the borehole logging. The geology observed from the borehole logs in the old workings was confirmed to be approximately the same geology in the area where the explosions were ignited and most of the measurements were taken. From the roof to 4.3 m (14 ft) and from 6.1 and 9.1 m (20 and 30 ft) is a fine-grained limestone. A shale/claystone formation is located between the limestone layers at 4.3 and 6.1 m (14 and 20 ft). The layers in the vertical borehole geology can be seen in Fig. 2.

2.2. Methane and coal dust explosions

The Lake Lynn Experimental Mine can accommodate a variety of explosion configurations. The explosions[1] can be located in A-, B-, C- or D-Drifts, and a typical explosion consists of natural gas (≈98% methane) injected into an ignition chamber at the face of the drift. Fig. 3 is a photograph of one of the ignition chambers at LLEM. A plastic diaphragm is draped across the entry to contain the methane in the ignition chamber. A photograph of a partially closed plastic diaphragm is shown in Fig. 4. An electric fan with an explosion-proof motor housing mixes the natural gas with the air to result in an approximate 9.5% methane–air concentration (Weiss and Harteis, 2008a).

The flammable natural gas–air volume was ignited using a triple-point ignition source. This ignition source consisted of three sets of two 100-J electric matches that were equally spaced at mid-height across the closed end of the drift and ignited at the same time. To increase the explosion pressure, either the ignition chamber was lengthened or pulverized coal dust was suspended on shelves from the mine roof starting just outside of the ignition chamber (Weiss and Harteis, 2008a). A photograph of explosive

[1] Mine shot numbers 506–524 were conducted for purposes other than this study. Mine shot numbers 506–507 are referenced in Cashdollar et al. (2007) and Gates et al. (2007). Mine shot numbers 508–509 are referenced in Weiss and Harteis (2008a). Mine shot numbers 513, 514, and 516–19 are referenced in Weiss et al. (2008b). Mine shot numbers 523 and 524 are referenced in Millero (2008). Mine shot numbers 520–522 are not yet published; however, the work was completed by Ken Cashdollar, Eric Weiss, and Sam Harteis as part of the mine explosion program for NIOSH, Office of Mine Safety and Health Research's then Disaster Prevention and Response Branch.

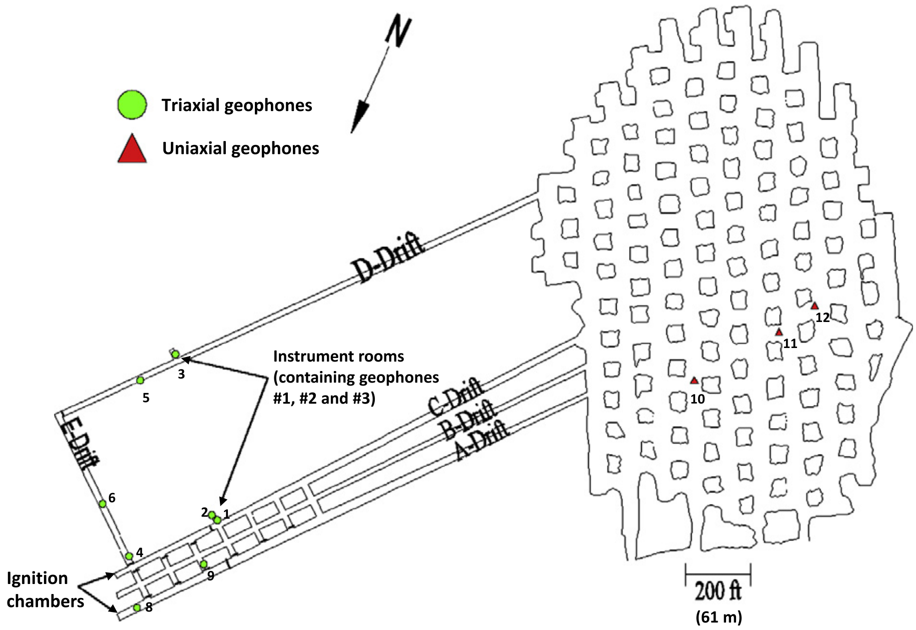

Fig. 1. Layout of the Lake Lynn Experimental Mine with geophone location, instrument room locations and ignition chamber locations highlighted.

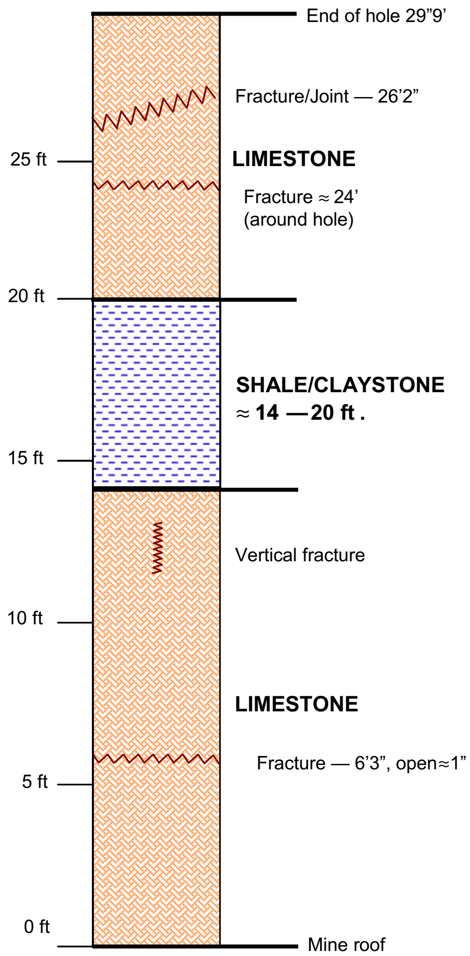

Fig. 2. Vertical borehole geology of the old workings at the Lake Lynn Experimental Mine. The layers detected in the old workings were considered to be consistent with the geology of the drift area.

Fig. 3. Ignition chamber located at the end of C-Drift. (Figs. 3–5 were provided by Eric Weiss of NIOSH, Office of Mine Safety and Health Research's then Disaster Prevention and Response Branch.)

Fig. 4. Plastic diaphragm used to contain methane within the ignition chamber.

coal dust and rock dust being suspended from the mine roof and placed on the floor is shown in Fig. 5.

For this study, the size of the explosion is defined as the peak pressure generated during the experiment. Pressure measurements were taken from the drift area in the mine. The data were sampled at 1500 samples per second and were obtained from the staff at the Lake Lynn Experimental Mine. The pressure measurements were not on the same time scale as the seismic measurements. An exam-

Fig. 5. Example of coal and rock dust being suspended from the mine roof and placed on the mine floor.

ple of a pressure–time curve is plotted in Fig. 6. The multiple curves represent the different instruments located throughout the drift area in the mine. The peak pressure generated for the example in Fig. 6 is around 55 psi (0.38 MPa), which would be considered as the size of that particular explosion. A total of 16 explosions were analyzed for this paper. In some cases, an explosion containment seal was in the propagation path of the explosion. Fig. 1 indicates the location of the explosion containment seal in the A- or C-Drift entry and the location of mine seals in the crosscuts, which are all represented by small thick black lines. The seals in the propagation path of the explosions were approximately 115 m (375 ft) away from the face of the drifts. In most scenarios during the study, seals were also constructed in the crosscuts between A- and B-Drifts and B- and C-Drifts.

2.3. Seismic transducers

Geophones were chosen as the seismic transducer to record seismic waves emanating from the methane and coal dust explosions and were placed in locations to surround the area of these explosions. All geophones were located on the mine roof except for one, which was located in the C-Drift instrument room floor (geophone #1 in Fig. 1). Both the triaxial and uniaxial geophones had a natural frequency of 4.5 Hz. The output chart provided by the manufacturer only includes responses up to 90 Hz; nevertheless, for this study, it was assumed the response was constant but that spurious responses could occur.

Surface measurements above the mine were taken near the end of the study using a three-component digital output seismometer. The instrument was installed at a depth of one meter on the surface above the A-Drift face shortly before mine shot number 523. The instrument was set to sample at 500 samples per second and was oriented in the same manner as the geophones installed inside of the mine. Data from this seismic instrument were only available for mine shot numbers 523–524.

2.4. Seismic monitoring system

The seismic monitoring system was installed within the existing structure of the Lake Lynn Experimental Mine. The two A/D converters used in the study, named MS boxes and QS boxes, both had a sampling rate of 2000 samples per second and contained six channels for input. The MS boxes had 22-bit resolution (14-bit A/D with 8-bit gain) and the QS boxes had a 24-bit resolution. Throughout the project, the seismic system utilized four MS boxes and four QS boxes. Due to licensing agreements with the manufacturer, a maximum of 10 triaxial or 30 uniaxial geophones, or a combination of both, could be connected to the seismic system. The seismic monitoring system was a trigger-based system, in contrast to a real-time continuous monitoring system. This system only recorded and saved data based upon two or more geophones being triggered by an event.

2.5. System calibration

In order to estimate the radiated seismic energy, the seismic system needed to be calibrated to determine the total system response to ground velocity. In some instances this step would be unnecessary—for example if the manufacturer's commercial software were used—however, the more manually based "step-by-step" analysis of the signatures was necessary for the study. With the manufacturer's existing commercial software, certain assumptions made during the seismic analysis in background processes would have been unknown, and it was determined that better observations and conclusions would result if all the assumptions made during the calculations were identified. Therefore, spreadsheets using visual basic code were created by the authors and other NIOSH engineers were used to analyze all the seismic signatures.

The calibration of the seismic system helped to measure digital counts for a 1-V input signal as a function of frequency. This measurement, called the digitizer constant *C*, was used to determine

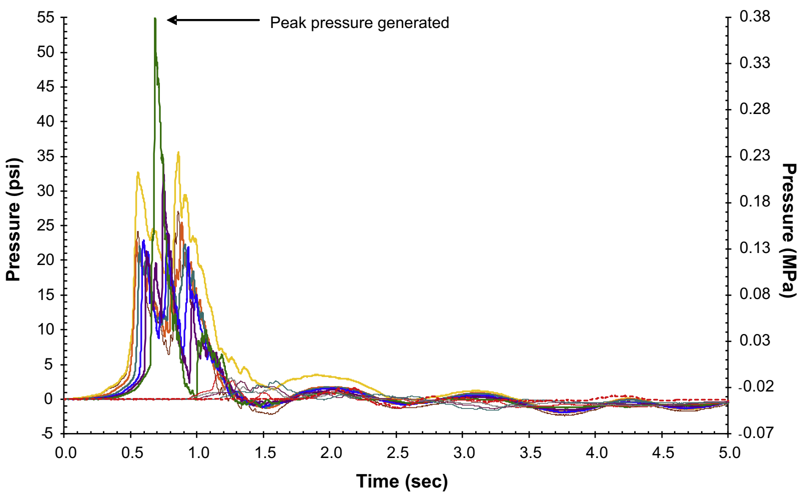

Fig. 6. Example of pressure–time curves used to obtain the size of the explosion, as defined by the peak pressure generated.

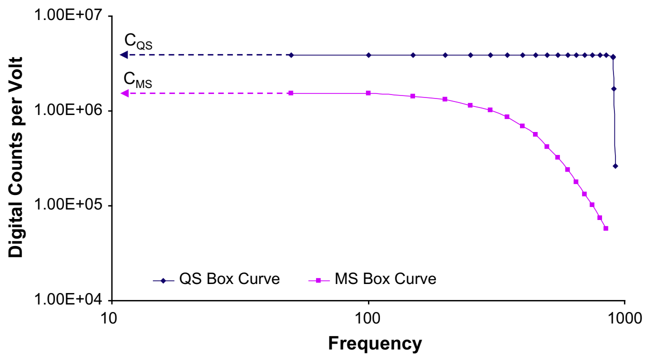

Fig. 7. Calibration results for both MS and QS boxes.

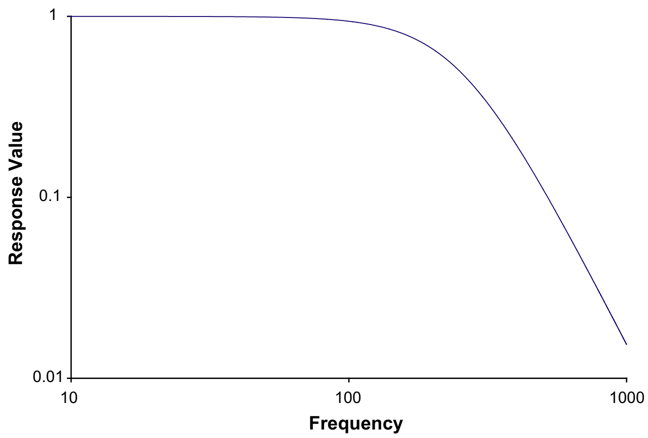

Fig. 8. Filter response, $G(\omega)$, for MS box.

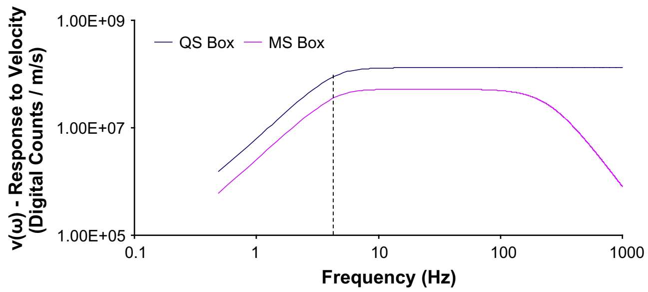

Fig. 9. Complete system amplitude response to ground velocity, $V(\omega)$. The natural frequency of the geophone is highlighted by the dotted line at 4.5 Hz.

total system response to ground velocity. In turn, the total system response to ground velocity helped determine the radiated seismic energy. To obtain the digitizer constant, the peak-to-peak amplitude of a 2-V signal was generated by a signal generator and measured by the seismic system at different frequencies. The signal generator was checked by an oscilloscope to maintain a constant 2-V signal and a multimeter was used to validate each frequency. The response to each calibration frequency, between 50 and 1000 Hz at 50-Hz intervals, was digitized by both the MS and QS boxes and then plotted. The results and calibration points of each specific frequency are shown in Fig. 7.

The digitizer constant is where each curve intersects the *y*-axis. The values of the digitizer constant were $1.54e10^6$ counts/V for the MS box and $3.85e10^6$ counts/V for the QS box. The responses of the anti-aliasing filters for each digitizer are also observed in Fig. 7. The QS box had a constant response at both low and high frequencies. The sudden change in high-frequency response of the curve is due to the anti-aliasing filter near the Nyquist frequency of 1000 Hz. This response was to be expected since the A/D converter collects 2000 samples per second.

The results for the MS box show a constant response at low frequencies up to approximately 100 Hz. The loss in amplitude at higher frequencies is due to an anti-aliasing low-pass filter built into the MS box. The amplitude response at higher frequencies can be modeled based upon the calibration response. The amplitude response of the low-pass filter, defined as $G(\omega)$, was derived and is shown in the following equation:

$$G(\omega) = \frac{1}{1 + \left(\frac{\omega}{\omega_c}\right)^3} \tag{1}$$

where $\omega = 2\pi f$, f is the frequency in Hz, and $\omega_c = 2\pi f_{corner}$, f_{corner} is the frequency in Hz.

The corner frequency of the filter was found to be around 250 Hz. The resulting filter response is plotted in Fig. 8. The filter response is constant up to approximately 100 Hz, then changes as a result of the anti-aliasing filter inside the MS box.

Once the number of digital counts for a 1-V signal had been identified for each digitizer, the system amplitude response to velocity was derived based upon the previous calibration results and specification sheets of the geophones provided by the manufacturer. The instrument response of the geophone was derived using a single degree of freedom damped spring-mass system model (Aki and Richards, 2002) and the Sercel geophone product sheet (Sercel, 2005). The system amplitude response to ground velocity, defined as $v(\omega)$, is shown in Eq. (2) and is plotted in Fig. 9.

$$v(\omega) = \left(\frac{EC\omega^2 \left(\frac{R_s}{R_t}\right)}{\sqrt{\left(\omega_o^2 - \omega^2\right)^2 + \left(2h\omega_o\omega\right)^2}} \right) G(\omega) \tag{2}$$

where E is the geophone electrodynamic constant (V/m/s), C the digitizer constant, determined from a sinusoidal input test (digital counts/V), $\omega = 2\pi f$ (frequency in Hz), R_s the shunt resistance for a given damping (Ω), R_t the total circuit damping (Ω), $\omega_o = 2\pi f_{natural}$ (natural frequency in Hz), and h is the geophone damping.

The asymptotic slope below the natural frequency has a value of 2 and a value of 0 after the natural frequency, agreeing with the expected amplitude frequency response to velocity for a geophone (Havskov and Alguacil, 2006). For the MS box, the response changes near 100 Hz due to the anti-aliasing filter.

The geophone cables used during the calibration process were not the specific cables used in the mining environment during the study. However, the cables used during the calibration and in the mine were of the same type. The length of geophone cable used in the mine was well under the limits of the manufacturer's recommendation, so it is assumed that the cables in the mining environment had no adverse effect on the seismic signatures.

2.6. Calculation of radiated seismic energy

The radiated seismic energy, E_s, is expressed in units of joules and is defined in Eq. (3) (Boatwright and Fletcher, 1984).

$$E_s = 4\pi\rho c R^2 (I_1 + I_2 + I_3) \tag{3}$$

where ρ is the density of the rock at the source (kg/m^3), R the distance from source to receiver (m), c the P- or S-wave velocity (m/s), and I is the integral of squared velocity for a geophone orientation (m^2/s^2/Hz).

The radiated seismic energy relationship used in this study is a simplified version from the equation derived in Boatwright and Fletcher (1984). Rock drop tests were conducted in the mine to

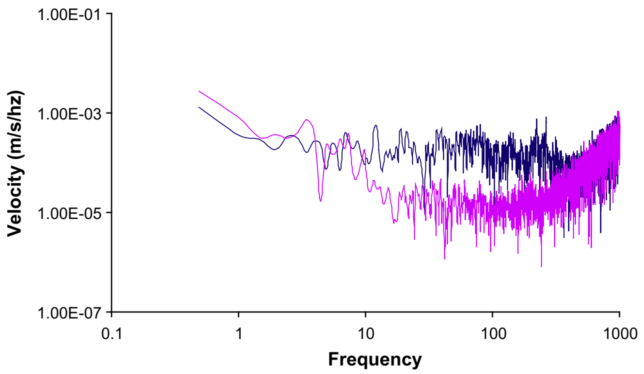

Fig. 10. Example of the Fourier amplitude spectrum of ground velocity, $V(\omega)$. The blue line represents the signature from the event and the pink line represents the background noise.

obtain values for the P- and S-wave velocities. The P- and S-wave velocities were calculated to be 4511 m/s (14,800 ft/s) and 2604 m/s (8545 ft/s). These values are in the same velocity range as determined for another limestone formation in Pennsylvania (Iannacchione et al., 2005a).

For this study, I was calculated using the Fourier amplitude spectrum of ground velocity, which is a similar method from Iannacchione et al. (2005a). The Fourier transformation of a seismic signature was defined as $S(\omega)$. This dataset can be divided by the instrument correction $\upsilon(\omega)$, defined earlier in Eq. (2). The result is $V(\omega)$, which is the Fourier amplitude spectrum of ground velocity in units of m/s/Hz, as shown in the following equation:

$$V(\omega) = \frac{S(\omega)}{\upsilon(\omega)} \tag{4}$$

An example of the Fourier amplitude spectrum of ground velocity is shown in Fig. 10. The blue[2] line represents the amplitude spectrum of ground velocity for the explosion. The pink line represents the amplitude spectrum of velocity for the background noise. This was calculated from a portion of the seismic signature prior to the explosion. On the left side of Fig. 10, the two curves are approximately parallel and of similar value. Between approximately 10 and 300 Hz, they are separated, and on the right side of the figure they are completely merged. The separated area between signal and noise curves is squared and represents the integral of squared velocity needed for calculating the radiated seismic energy. When the signals are merged, it means that the signal-to-noise ratio is very low and thus the energy from that specific frequency has approximately the same amount of energy in both the signal and background noise. A signal-to-noise ratio criterion of at least 3 was taken into consideration when calculating the integral of squared velocity, with a similar criterion used in Iannacchione et al. (2005a). A program was coded to calculate the integral of squared velocity I. The program squared the value of $V(\omega)$ for both the signal and noise curves, then substracted $V(\omega)$ of the noise from the signal at each frequency. The results were summed up and the summation represented I. This summation also represents the area found between the signal and noise curves in Fig. 10. The parameters for I_1, I_2, and I_3 represent the three axis on the triaxial geophone.

3. Results

The calibration of the seismic system helped develop the formulas and methods used for calculating the radiated seismic energy estimates for the mine shots. For this study, a total of 16 explosions were monitored. Mine shot numbers 506–509 were conducted in the C-Drift entry (Fig. 1). Mine shot numbers 510–524 were conducted in the A-Drift entry (Fig. 1). Five tests were conducted where an explosion-containment seal was in the path of the explosive wave: mine shot numbers 506, 508, 509, 523 and 524. For two of these five tests—mine shot numbers 506 and 509—the explosion caused the seal to fail. A tabulated summary of the size of the explosion, the initial explosive energy, the radiated seismic energy, and the percentage of the initial energy for mine shot numbers 506–524 can be viewed in table 1.

Table 1
Tabulated summary showing the size of the methane and coal dust explosion, initial explosive energy of the methane and coal dust explosion, radiated seismic energy calculated from the data, and the percentage of the original energy found in the seismic energy.

	Pressure (MPa)	Initial energy (MJ)	Radiated seismic energy (MJ)	% of initial energy
Mine shot #506	0.617	799	26.60	3.33
Mine shot #507	0.147	710	14.41	2.03
Mine shot #508	0.346	710	9.59	1.35
Mine shot #509	0.631	1525	24.58	1.61
Mine shot #510	1.101	511	0.29	0.06
Mine shot #513	0.096	511	0.12	0.02
Mine shot #514	0.103	511	0.68	0.13
Mine shot #516	0.090	511	0.17	0.03
Mine shot #517	0.093	511	1.00	0.19
Mine shot #518	0.092	511	0.07	0.01
Mine shot #519	0.172	1085	2.17	0.20
Mine shot #520	0.107	511	1.72	0.34
Mine shot #521	0.011	511	0.0029	0.00057
Mine shot #522	0.109	511	1.72	0.34
Mine shot #523	0.309	638	11.54	1.81
Mine shot #524	0.552	1085	18.86	1.74

The method to estimate the size of the explosion in relation to pressure is explained in Section 2.2. The estimates of the initial explosive energy are based upon the amount of coal dust and methane gas reported from the mine shot summaries obtained from the Lake Lynn Experimental Mine staff. The combustion properties of methane were needed to provide a factor to relate the volume of methane to an energy value. For methane, the heat of combustion was found to be 50 MJ/kg (Gexcon, 2006). Consultation with experienced engineers at NIOSH, who have extensively studied methane explosions, verified that the same factor could be used to estimate the amount of energy contained within the coal dust. For some of the mine shots, the coal dust was mixed with rock dust. In these instances, the amount of coal dust was not considered in the initial explosive energy estimation because the rock dust concentration considerably weakened the explosion.

The size of the explosion was not exclusively based on the amount of initial methane and coal dust. Containment within a sealed area or the placement of electrical matches in relation to the mine face in the ignition zone could cause larger peak pressures. The radiated seismic energy estimations are considered to be relative values between the different experiments. It is possible

[2] For interpretation of color in Figs. 7, 9, 10, the reader is referred to the web version of this article.

that due to the proximity of the geophones to the explosion, the radiated seismic energy values were calculated from P-waves, S-waves, and surface waves, since these waves had little time to separate in the waveform. If the seismic energy had been measured from a borehole further away from the explosion, a more absolute value of energy could have been calculated.

4. Discussion

4.1. Estimated energy as a percentage of the original energy

The amount of seismic energy from an explosion is typically less than 1% of the original energy of the source (Perret, 1968). The final column in Table 1 shows the percentage of the initial seismic energy of the methane and coal dust explosions from the initial explosive energy. In all cases where the percentage of initial explosive energy was less than 1%, the explosion did not have an obstruction in its path as it propagated down the drift. The degree of decoupling of the methane explosion to the limestone is believed to be a significant factor in the transfer of seismic energy into the rock. The methane explosion is ignited in an open space and the transfer of the energy occurs as the expanding pressure wave interacts with the surrounding rock. This is very different from other types of seismic sources such as an earthquake or a roof fracturing in an underground mine where the source is direct rock-on-rock contact. Because the pressure wave is not coupled well with the surrounding rock, the transfer of seismic energy from methane explosions into the rock is significantly less than other mining-related mechanisms that create seismic energy.

In five of the six cases studied where the percentage of initial explosive energy was greater than 1%, the explosion was either contained within a sealed area or the explosion caused a seal failure. This suggests that an explosion contained within a sealed area or the destruction of a seal by an explosion can result in a large transfer of seismic energy. For example, mine shot numbers 519 and 524 each contained the same amount of initial explosive energy; however, the containment of the explosion within a sealed area for mine shot number 524 shows a much larger peak pressure generated and a greater radiated seismic energy estimate. The source of additional seismic energy is believed to originate from the explosive wave coming into contact with the explosion-containment structure. The explosion-containment structures are keyed directly into the ribs of the mine entry, which explains the source of the additional seismic energy.

In the sixth case, involving mine shot number 507, there was no seal in the path of the explosion; however, the initial energy was over 1%. For this particular shot, a geophone close to the source could have been affected by the air blast. Geophone #1, on the cement floor in the C-Drift instrument room, recorded eight times more energy than geophone #2, which was in the same instrument room but on the roof further away from the explosion. Geophone #1 was approximately 1.2 m (4 ft) away from the acoustic air blast, while geophone #2 was approximately 4.6 m (15 ft) away from the air blast. The data from geophone #1 were most likely affected by the air blast passing by, and this caused a large energy estimate for mine shot number 507.

4.2. Relationship between the radiated seismic energy and size of the explosion

Different methods of analyzing seismic data include studying the amplitude, duration, and frequency content of a particular seismic signature. The radiated seismic energy, as calculated by Eq. (3), takes these parameters into account by considering the integral of squared velocity. The radiated seismic energy equation is also derived from physical characteristics of the environment such as the medium density and the seismic wave velocity. Since this single equation takes into account the significant parameters observed during this study, a relationship between radiated seismic energy and size of the explosion was derived. The size of the explosion, defined as the peak pressure generated, is characterized by experimental setup parameters such as the mine geometry, presence of an explosion-containment seal, and the amount of explosive methane and coal dust used. Previous seismic studies have found a power relationship between the size of underground blasts and seismic parameters (Willis and Wilson, 1960; Jalinoos and White, 1986). Therefore, for this study a power relationship between the radiated seismic energy and peak pressure generated was assumed.

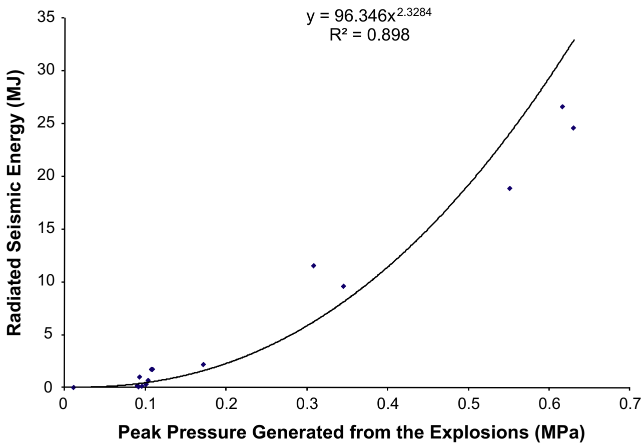

Fig. 11. Power relationship of the radiated seismic energy versus size of the explosion for all the mine shots observed.

Fig. 11 shows the correlation between the radiated seismic energy and size of the explosion. The correlation coefficient for this trend is 0.90. In order to estimate the size of the explosion based upon an estimated radiated seismic energy, the following relationship in Eq. (5) was derived from the trend in Fig. 11.

$$P = \left(\frac{E_s}{96.35}\right)^{\frac{1}{2.33}} \tag{5}$$

where P is the peak pressure of the explosion (MPa), and E_s is the radiated seismic energy (MJ).

A more detailed relationship of the estimated energy and the size of the explosion, which integrates both Eqs. (3) and (5), is reported in the following equation:

$$P = \left(\frac{4\pi\rho c R^2 (I_1 + I_2 + I_3)}{96.35}\right)^{\frac{1}{2.33}} \tag{6}$$

where P is the size of the explosion (MPa), ρ the density of the rock at the source (kg/m^3), R the distance from source to receiver (m), c the P- or S-wave velocity (m/s), and I is the integral of squared velocity for a geophone orientation (m^2/s^2/Hz).

Two important considerations to take into account about Eq. (6) are that the relationship is based upon relative radiated seismic energy estimations (as opposed to absolute values) and the scaling differences between the Lake Lynn Experimental Mine and an actual active mine. The radiated seismic energy estimations are relative because there are some unknowns in the data that are due to the placement of the geophones. For example some geophones were so close that a full distinction between P-, S- and surface waves could not be made because they had not had enough time to separate. Also, because of all the crosscuts in the drift area of LLEM, the seismic waveforms might have included reflections of the pressure wave in the crosscuts. Therefore, while the radiated seismic energy estimations might not be the exact value, they can be related to one another based upon the size of the explosion. There is a vast volumetric difference between the drifts at LLEM versus a sealed off area in a mine. A 0.14-MPa (20-psi) explosion occurring at an underground mine would contain more energy compared to a 0.14-MPa (20-psi) explosion occurring at the test facility where the measurements were made. To generate a 0.14-MPa (20-psi) explosion within a larger volumetric area, more energy needs to be involved in creating that event.

5. Conclusions and recommendations

Seismic signatures emanating from controlled methane and coal dust explosions at the Lake Lynn Experimental Mine were studied. The objective was to analyze these signatures and to determine if the size of the explosion could be estimated from the radiated seismic energy recorded by the geophones. For this paper, a total of 16 explosions were analyzed. The explosions were experimentally different from each other in terms of the placement of explosion-containment seals and blast pressures generated by the methane and coal dust creating the explosion. These differences resulted in explosions contained within sealed areas, explosions freely propagating down a mine drift, and varying amounts of coal and/or rock dust used to fuel or weaken the explosions. A seismic system was installed in the mine and geophones were mounted on the mine roof or floor. Calibration of the seismic system was performed to estimate the radiated seismic energy from the explosions through a spreadsheet using visual basic code.

When the explosive wave was allowed to freely move down the mine drift, less than a percent of the original energy was transferred as seismic energy into the rock. The methane explosion was ignited in an open space and the transfer of the energy occurred as the expanding pressure wave interacted with the surrounding rock. Therefore, the transfer of seismic energy from methane explosions into the rock was significantly less than other mining-related mechanisms that create seismic energy. When there was an explosion-containment seal included in the experimental design, the transfer of seismic energy increased significantly. The seals were keyed directly into the ribs of the mine entry and were found to efficiently transfer seismic energy. The radiated seismic energy estimates calculated for each experiment were considered to be relative values. A power relationship was determined which related the radiated seismic energy to the size of the explosion, as defined by the peak pressure generated. The radiated seismic energy estimate took into account the seismic signature characteristics for each experiment while the size of the explosion was a function of the experimental design. The factors that most affected the seismic signatures were the mine geometry, the size of the methane and coal dust explosion, and the location of the explosion-containment structure.

During this study, the geophones were only anchored onto the surface of the mine roof or floor. A future consideration is having the geophones properly grouted in a borehole. This would allow for more accurate radiated seismic energy assessments since a better observation of P- and S-waves could be made. Another consideration involves having more control over the experimental variables. It is recommended for future research to simplify the experimental design so that unobstructed methane explosions of different sizes could be examined, independently of seal structures and crosscuts. Once this effort would be completed, a series of controlled explosions at varying sizes, using a controlled explosion-containment structure, could be evaluated. Following this, additional studies could be completed with explosion-containment structures that are structurally different and/or crosscuts could be introduced into the experimental design to examine the effect in the seismic signatures.

The research conducted in this study simply presents the first step in collecting seismic signatures from underground explosions, and the preliminary results identify the potential for seismic data to be used in forensic studies of mine explosions such as the Sago Mine disaster. It is believed that this research shows there is a relationship between the size of an underground explosion and the radiated seismic energy. If more controlled experiments are conducted and a scaling factor between the Lake Lynn Experimental Mine and an operating coal mine is found, it is possible that seismic records from seismic monitoring stations can estimate the pressure generated by an underground coal mine explosion.

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