Detonation wave propagation in underground mine **e**ntries

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ABSTRACT: A series of explosive detonation experiments was conducted in NIOSH's Bruceton and Lake Lynn Experimental Mines to evaluate low level (<6 psig) detonation wave propagation behavior in single and multiple entry configurations. Entry cross-sectional area varied from 5 to140 m^2 and explosive weights of Pentolite ranged from 0.24 to 2.4 kg. Behavior of the detonation wave was evaluated through recording of the pressure as a function of time and distance from the explosive detonation in single and multiple entry interconnecting tunnels. Peak pressure from detonation of an explosive in an underground mine maintains magnitude for a greater distance than is the case on the surface and is shown to follow the simple scaling relationship $P = 702.8(W/V_t)^{0.514}(0.65)^n$, where P is the peak detonation pressure in kPa, W is the weight of the explosive charge in kg, V_t is the total volume in m^3, and n is the number of splits, n = 0, 1, 2, …n. The total energy, or impulse, I, generated by these detonations can be expressed as $I = 1.34(W/A)0.64^n$, where W is the weight of the explosive charge in kg, A is the area of the main tunnel in m^2, and n is the number of side entries, n = 0, 1, 2, …n.

1 INTRODUCTION

When considering the behavior of detonation waves in a confined region, one deals with the mode in which a detonation wave and its driver gases expand. In a free field, this spherical shock expansion is readily calculated and shown to follow a rather simple Sachs ($D/W^{1/3}$) scaling law. However, inside a tunnel that is strong enough to withstand the explosives' forces, the pressure measured at any given distance from the point of detonation does not have an obvious relationship with the explosive yield, since the spherical shock wave is interrupted by the interaction with the tunnel. The shock front pressure attenuates because of the rarefaction wave that degrades the front and because of the interaction between the moving gas and the confining walls. This viscous interaction is implicit in all detonation attenuation in tunnels in varying degrees depending upon the duration of the wave, the diameter and roughness of the tunnel, and the density, velocity, and viscosity of the gas. To completely characterize these shock pressure interactions would require 3-dimensional hydrodynamic codes and the results would be limited in practical utility for mining engineers and mine operators.

The mining engineer needs to be able to simply and accurately predict the behavior of low pressure detonation waves inside mine tunnels to effectively design underground ventilation control structures. In underground metal and nonmetal mines, these structures need to be able to withstand the air detonation pressure and impulse associated with routine development and production blasting. These experiments were conducted to determine the attenuation of the peak overpressure and the detonation wave behavior from interactions with adjacent crosscuts as the pressure wave travels through mine openings of various cross-sectional areas. The pressure waves in these experiments were produced with the unconfined detonation of various size explosive charges of Pentolite near the closed end of experimental tunnels with cross-sectional areas ranging from 5 to 140 m^2.

1.1 *Background*

Since World War II, there have been numerous investigations of the propagation of air detonations on the surface, but few reported studies have been done on the propagation of air detonations in an underground environment. Taylor (1968) presents an overview of detonation wave behavior in confined regions with a specific emphasis on structure design for the storage of fuels and explosives in tunnels, chambers and tunnel junctions. Curran (1966) collected data and established a pressure-distance relationship for various explosives weights in single entry tunnels ranging from 5 cm to 8 m in diameter. These results showed that the pressure could be expressed as

$$P = (W/D*d^2)^{0.8} \qquad (1)$$

where W = charge weight; D = the distance from the charge; and d = the diameter of the tunnel. Peak overpressures ranged from about 350 to 7,000 kPa.

Weibull [1968], from the Royal Swedish Fortification Administration, conducted many experiments in partially closed chambers to measure the peak pressure from the detonation of TNT charges. The main purpose of these tests was to provide the basis for developing a nuclear detonation simulator to compare peak pressures and durations of detonation waves. To produce detonations of long duration, four partially closed chambers were used, in which TNT charges of different weights were detonated. The results showed that the pressure correlated with the charge weight to volume ratio,

$$P = K*(W/V) \qquad (2)$$

where W = the weight of the charge and V = the volume of the chamber. The fit of the experimental data to this relationship is fairly good. This straight line was empirical and was not founded theoretically.

Most explosives, upon detonation, release from 1,000 to 1,200 kcal/kg of explosive. Therefore, the charge weight to volume ratio can be considered as an energy density of kcal per unit volume. For the same mass of charge, the energy release should show a continual increase in overpressure with decreasing chamber volume. The basic approach in this study was to consider the explosive energy to heat up the explosive gas to equilibrium values of pressure and temperature. The explosive gases are treated as ideal and are obtained from the ideal gas law:

$$P = E\ (\gamma-1)/V \qquad (3)$$

where P = pressure; E = the internal energy of the gas; γ = the ratio of specific heats; and V = the initial volume of the containing chamber. E is taken to be the chemical energy of the explosive and is equal to WQ, where W is the mass of explosive. Q is about 1100 – 1200 cal/g for most explosives. Equation 2 can then be written in terms of pressure as:

$$P = (W/V)\ Q\ (\gamma-1) \qquad (4)$$

Equation (4) suggests that the equilibrium pressure from the detonation of a particular explosive should scale with the ratio of W/V where V is considered the expansion volume through which the explosive energy is deposited.

The current study was conducted to explore the utility of extending this simplified charge mass/volume scaling relationship for peak overpressures up to 40 kPa, and determine the decay in peak pressure with distance and the impulse behavior for both single and with parallel entries with interconnecting cross-cuts. Given a peak pressure at one location, this method could be used by a mine operator to predict the peak overpressure and impulse that one might expect at a given location outby the source of the detonation. Such relationships are also useful for predicting the safe stand-off distance for secondary rubble blasting underground to reduce the exposure of underground workers to damaging air-detonations. Such data can also be used by accident investigators to re-construct explosion events and locate the origin of the explosion based on detonation pressure damage along the various paths of propagation. The current emphasis of this study, however, is to provide ventilation engineers with a simple, reliable method to predict low-level detonation overpressures and impulses as a function of distance and charge weight from routine underground production blasting. Such methodology can aid in the design of air-blast resistant and economical ventilation control structures used for coursing fresh air to various working sections of the mine.

2 EXPERIMENTAL

Experiments were conducted in the NIOSH Lake Lynn Experimental Mine (LLEM), the NIOSH Bruceton Experimental Mine (BEM), and on the surface at NIOSH's Lake Lynn Laboratory facility (Triebsch 1990). The Lake Lynn Laboratory (LLL) is a unique mining research laboratory designed to provide a modern, full-scale mining environment for the testing and evaluation of mine health and safety technology. Although the facility was developed with mining research in mind, it also serves as an ideal facility for the study of a wide range of explosion or fire phenomena in underground or confined spaces. The LLL consists of both surface and underground test sites and is sufficiently isolated from residents to allow mine/tunnel fire research and large-scale explosion testing of gases, dusts, and chemicals. The underground mine entries were developed adjacent to an abandoned commercial limestone quarry and underground limestone mine. The entries of the abandoned limestone mine, labeled as the old workings in figure 1, are approximately 5 m wide by 9 m high. The LLEM contains 5 drifts, shown in figure 1 as A, B, C, D, and E. These entries were developed to approximate the size of a typical Pittsburgh seam coal mine, about 6 m wide by 2 m high, and range from 200 to 500 m in length. The entries, in conjunction with the novel use of two explosion-proof bulkhead doors that can be positioned to open or close an entry, can be made to

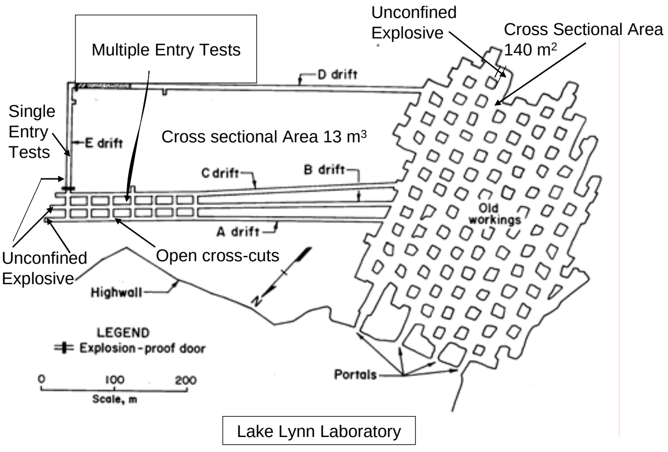

Figure 1. The Lake Lynn Experimental Mine (LLEM).

simulate room-and-pillar and longwall mine configurations.

The BEM, shown in figure 2, is an underground research facility located at Bruceton Pa. The BEM has been used since 1910 to conduct gas and dust explosion research focused on improving mine safety. The BEM consists of smaller entries that are about 2.7 m wide by 1.8 m high and about 400 m long. Experiments in the BEM single entry and the LLEM larger entries allowed the development of geometric size scaling relationships for modeling the pressure decay with tunnel distance and tunnel cross-sectional area, and with added cross-cuts. For the surface experiments, a Pentolite explosive charge

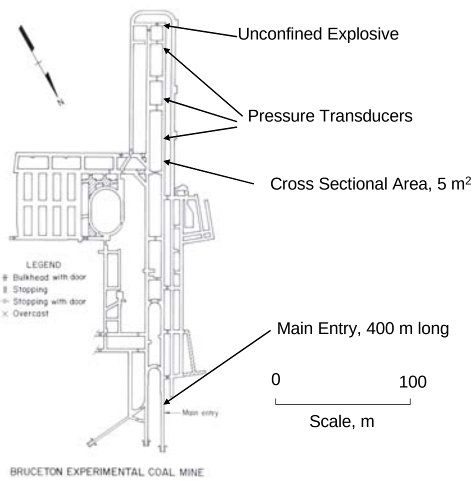

Figure 2. Bruceton Experimental Mine (BEM)

ranging from .24 to .45 kg was detonated 1.8 m from the Lake Lynn quarry floor. For all the underground experiments, a Pentolite explosive charge, ranging from .24 to 2.4 kg, was detonated in the center of the entry, one entry width from the closed end of the tunnel. The pentolite explosive charges up to 0.45 kg were single cast explosive boosters. For experiments using explosive charges up to 1 kg, combinations of .24 and .45 kg cast boosters were ganged together using tape. In the experiments using 2.2 kg of pentolite, two different geometrical configurations of 0.45 kg cast boosters were used. In one configuration, 6 or the 0.45 boosters were ganged together. In the other configuration, 6 of the 0.45 kg boosters were taped together vertically, forming a linear explosive charge.

To conduct experiments in the E-drift, the movable bulkhead was closed and the explosive was detonated in the center of the entry about 3 m from the closed end. The experiments in the BEM single entry and the E drift were conducted because they permitted the observation of the pressure wave propagation through single tunnels of 5- and 13-m^2 cross-sections without side branches. Experiments were also conducted in the multiple entry sections of the Lake Lynn the new and old workings, to observe the effect of pressure venting on the peak pressure as the pressure pulse propagated through the cross-cuts into the parallel entries. For example, if the explosive charge was detonated in the closed end of the A drift entry, the pressure wave in A-drift would propagate from the closed end and some of the energy would be vented into B-drift as the wave passed through each intersection. Experiments in B-drift permitted venting into both A and C drifts reducing the peak over pressure with each passing cross-cut.

3 INSTRUMENTATION

Near field pressure pulses were recorded using Endevco[1] (Model 8530C-15) piezo-resistive absolute pressure transducers with a range of 0-100 kPa or 0- 350 kPa and a resonance frequency of 180,000 Hz. The signal from each transducer was amplified by an Endevco (Model 136) DC amplifier with a 40 kHz filter. Additionally, B&K (Model 4036) microphones were used when maximum pressures were expected to less than 3 psig. The transducers and microphones were housed in a blunt cylinder, which was wrapped with 15-cm thick foam and mounted on tripods, shown in figure 3, at the geometric center of the entry cross-section at distances from the explosive ranging from 8 to 425 m. The sensor mounting followed recommendations from Walton (1981) for a blunt cylinder mount when making measurements in complicated detonation fields, where small errors in wave shape are preferable to large errors caused by misalignment. Since the sensing diaphragm is parallel to the direction of the detonation wave propagation, the resulting measurement can be considered as the static pressure. Data from the pressure transducers and microphones were recorded with a WINDAQ 720 A/D converter located up to 125 m from the transducers. Data was recorded at sampling rates ranging from 2000 to 66,666 samples per second per channel.

[1] Reference to a specific product does not imply endorsement by NIOSH.

Figure 3 Microphone housed in blunt cylinder and mounted on tripod.

3 RESULTS

3.1 *Surface Detonations*

Initial experiments were conducted on the surface at the LLL in order to ensure the validity of the instrumentation and analysis methodology. On the surface, the detonation wave propagates in a hemispherical fashion away from the charge. The volume of influence is

$$V_t = 2/3\ \pi\ D^3 \tag{5}$$

where D = the hemispherical radial distance from the point charge. Data from the surface shots correlated well with the charge to volume density, shown in figure 4, where

$$W/V_t \sim W/(2/3\ \pi\ D^3) \sim K\ (W^{1/3}/D) \tag{6}$$

This expression is the reciprocal of the conventional Hopkinson "cube root" scaling relationship for surface detonations of $D/W^{1/3}$.

3.2 *Single Entry*

Figure 5 illustrates a typical pressure history recorded by the pressure transducer for single entry experiments in the BEM and LLEM E drift. For this particular experiment, the pressure transducer was located 49 m from the 0.45 kg explosive charge detonated 3 m from the closed bulkhead door in the E drift of the LLEM. The time scale should be considered as relative time since time zero does not start with the detonation of the explosive. One can see the arrival of the leading edge of the shock wave closely followed by the reflected pressure pulse from the closed end. The reflected pressure wave traveled about 6.2 m further than the incident pressure wave and lags about 18 ms behind the incident pressure pulse.

The maximum peak pressure, usually the reflected pressure pulse, is plotted for the single entry experiments in figure 6 against the ratio of explosive charge mass to volume (W/V_t), where W is the explosive charge mass in kg and V_t is the product of the cross-sectional area of the mine entry in m^2 and the distance in meters from the closed end of the tunnel to the pressure transducer. The range of weights of explosive used for the single entry study ranged from 0.24 to 0.9 kg, while the single tunnel cross-sectional area ranged from 5 to 13 m^2. This simple correlation for a single entry fits the data quite well for experimental overpressures from 5 to 50 kPa. The best fit to the data was given by the use of the power formula as follows:

$$P = 702.8\ (W/Vt)^{0.514} \tag{7}$$

where P = the maximum pressure rise in kPa at the transducer, V_t is the product of the cross-sectional area of entry, A, in m^2, D is the distance from the closed end of the tunnel in m, and W is the explosive charge weight in kg. The fit has a correlation coefficient, R^2, of 0.968.

The results of the experiments show that for single entries or tunnels, the peak pressure for explosives detonated in free space decays with distance to the - 0.514 power for maximum pressures up to50 kPa, at distances from 25 to 425 m.

4 TUNNELS WITH SIDE BRANCHES

To study the detonation wave pressure decay in entries with single and multiple side branches, experiments were conducted in the A and B drifts and the old workings of the LLEM. A schematic of the experiments is shown in figure 7. Explosive charges ranging from .24 to .45 kg in A drift and .24 kg in B drift were detonated 3 m from the closed end and the pressure measured at various locations away from the detonation. In the old workings, explosive charges ranging from .48 to 2.4 kg were detonated 3 m from a closed entry and the pressure measured downstream from the detonation. Figure 8 shows the plot of the peak pressure before the intersection, or incident pressure, versus and the peak pressure after the intersections, or transmitted pressure. The incident pressure directly across the intersection was found to be relatively constant over the pressure range of study and is about 65% of the peak pressure upstream of the intersection for both single and double splits, as shown by the slope of the best fit line.

These results are somewhat consistent with studies at higher incident pressures ranging from 50 to 1700 kPa (Taylor 1968). Taylor's data shows that the transmitted shock pressure downstream of an intersection is about 75% of the incident shock pressure upstream of the intersection for both single and double branches. The resulting side branch shock pressure is about 35% of the incident shock pressure upstream of the intersection for both single and double branches in our study. This sharp pressure drop in the side tunnel would indicate to the mine ventilation engineer that the strength of the ventilation control structure would be about one-third that necessary to resist the detonation pressure in the main tunnel. It is also shown that unless these side tunnels are long, there will be reflected pressure that exceeds the side on pressure in the main tunnel. However, the weakness of ventilation control structures that are drag sensitive (flex with loading) can be improved by positioning them in the short side tunnels, because the dynamic pressure impulse is reduced. In addition, there are other key advantages for placing ventilation control structures in side branches to blasting to protect structures from the fly rock produced during production blasting.

Since it has been shown that the pressure loss across an intersection is constant, the downstream line-of-site- pressure should be a function of the weight of the explosive charge and the distance from the charge, as expressed in equation (7), and the number of intersections between the charge and the measuring location. Correcting the pressure drop in the main tunnel for the influence of side branches by the use of the factor from figure 7 as $(.65)^n$

$$P = 702.8\ (W/Vt)^{0.514}\ (.65)^{n}, \qquad (8)$$

where, P = the maximum pressure rise in kPa at the transducer, V_t is the product of the cross-sectional area of entry, A, in m^2, D is the distance from the closed end of the tunnel in m, W is the explosive charge weight in kg, and n is the number of intersections between the explosive and the measuring location.

The experimental peak pressure from the single entry detonations and those conducted in the entries with side branches is plotted in figure 9 against the predicted peak pressure using equation 8. The measured pressure agrees quite well with the predicted pressure, with the fit having a correlation coefficient, R^2, of 0.9703.

4.1 *Impulse*

Another important parameter in designing underground ventilation control structures is the total energy, or impulse, generated by these detonations. While the peak pressure decays with distance from the charge, the total energy of the detonation is generally conserved over the length of the tunnel. This can be seen in figure 10, where the pressure, in kPa, and the impulse, in kPa-s, are shown 23, 46, and 91 m from the explosive charge as a function of time. The peak pressure decreases from 72 to 38 to 26 kPa at 23, 46, and 91 m, respectively, while the impulse remains constant at about 0.1.5 kPa-s at each location.

The impulse, I, measured in a tunnel should be proportional to the mass of the explosive and the cross-sectional entry of the tunnel in which the explosive is detonated:

$$I = k\ (W/A) \qquad (9)$$

where W = the weight of the explosive in kg, and A = the cross-sectional area of the tunnel in m^2. Figure 11 shows the impulse as a function of W/A for all detonations in single entry configurations in the LLEM and BEM mine experiments. The results show a good correlation, with a k equal to 1.34 and a R^2 of 0.9508.

Since most ventilation controls in underground mines will be in crosscuts incident to the pressure wave, it is important to know the impulse perpendicular to the primary detonation wave. The energy split in a single tunnel with 1 side branch is illustrated in figure 7. To determine the pressure at position D in the tunnel, one has to consider the loss of energy through the three preceding side branches. As the pressure pulse passes position $\mathbf{n_1}$ the energy splits. Some portion the energy vents through the side tunnel while the remainder continues down the tunnel towards $\mathbf{n_2}$. Again, the energy splits as it passes through $\mathbf{n_2}$ and $\mathbf{n_3}$. The energy split at each intersection in B drift is shown in figure 7c. As the pressure pulse passes position $\mathbf{n_1}$, and each succeeding intersection, the energy splits three ways, two perpendicular to the main tunnel and the remainder continuing down the main tunnel. The energy split in the LLEM large-opening area is shown in figure 7d. In this set-up, the side tunnels were staggered so the energy splits by one-half at each intersection with a side tunnel.

Table 1. Impulses before and after intersections in single entries with side branches

Drift	Before Intersection	After 1st Intersection	After 2nd Intersection	After 3rd intersection
A	.153	.096 (60%)	.059 (62%)	.044 (74%)
B	.028	.020 (71%)	.0012 (62%)	
Large Opening	.069	.041 (57%)	.025 (63%)	

Table 1 shows the averages of all the transmitted impulses across an intersection in the A and B drifts and the LLEM large-opening area. The percent transmitted ranged from 57% to 74% with an average of 64%. This agrees with the results for the pressure loss across these intersections, which averaged about 35%, or 65% transmission. Thus, the impulse in a side branch can be stated as:

$$I_{incident} = 0.36 * I_{total} \qquad (10)$$

The impulse in the main tunnel can then be expressed from equation 9 as:

$$I = 1.34\ (W/A)\ (.64)^{n} \qquad (11)$$

where W = the weight of the explosive charge in kg; A = the area of the main tunnel in $m^{2;}$ and n = the number of side intersections, n = 0, 1, 2, …n.

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6 SUMMARY

Peak overpressure from unconfined explosive detonations in tunnels decays much more slowly with distance underground and is influenced by the number of intersections. The total energy, or impulse, from these detonations remains generally constant with distance and is also in influenced by the number of intersections. Peak pressure decay from underground experiments conducted in the BEM and the LLEM was shown to correlate well with $P = 702.8(W/Vt)^{0.514}(.65)^{n}$. The impulse in a single entry tunnel with side branches correlated well with $= 1.34(W/A)(.64)^{n}$, where n = number of intersections, n = 0, 1, 2, …n, for unconfined charge weights, W, ranging from 0.24 to 2.4 kg and cross-sectional areas ranging from 5 to 140 m^2.

These relationships are useful to predict the behavior of low pressure waves inside mine tunnels from the unconfined explosive detonation as a function of tunnel distance, cross-sectional area, number of intersections, and weight of explosives to effectively design underground ventilation control structures. This relationship is also useful for predicting the safe stand-off distance for secondary rubble blasting underground to reduce the exposure of underground workers to damaging air-blasts. Such data can also be used by accident investigators to reconstruct explosion events and locate the origin of the explosion based on blast pressure damage along the various paths of propagation.

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