BLAST WAVE PROPAGATION IN UNDERGROUND MINES

by

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ABSTRACT

This project investigates the behavior of blast waves from the detonation of high explosives in an underground mine. A series of explosive tests was conducted in the underground and surface facilities at the Bureau of Mines' Lake Lynn Laboratory to evaluate the potentially dangerous effects of blast waves produced by open shooting, blown out holes, or accidental detonations of explosives. Shots of C4 and TNT were fired at the dead end of a 6 ft high by 20 ft wide entry, at the intersection of two entries, and on the surface. C4 and TNT were chosen for this research because they exhibit very consistent performance. Behavior of the blast wave was evaluated through recording of the pressure as a function of distance from the explosive detonation.

For both explosives, C4 and TNT, peak pressure decay with travel down the entry was inversely proportional to distance to the 0.9 power. When comparing pressure measurements at 200 versus 100 feet from the detonation; at 200 feet the pressure would be $1/2^{0.9}$ or 54 percent of that measured at 100 feet. By comparison, peak pressure for a surface shot exhibits a decay with distance to the -1.6 power, yielding a pressure at 200 feet $1/2^{1.6}$ or 33 percent of that measured at 100 feet. This result confirms that the blast wave from detonation of an explosive in an underground mine maintains its force for a greater distance than would be the case on the surface.

Table and figures follow the text.

INTRODUCTION

This report describes a study of the propagation of the blast from an unconfined explosive charge in an underground mine. Since World War Two there have been numerous investigations of the propagation of air blast on the surface but few studies have been done on the propagation of air blast in an underground environment. An early study of this topic was conducted in 1968 by Hanna and Zabetakis of the Bureau of Mines, who studied the blast wave propagation from unconfined TNT charges and modified amatol charges in an abandoned underground limestone mine. The authors found that the peak pressures followed the cube root (Sachs) scaling law within one tunnel diameter of the detonation; at greater distances the pressures were generally higher than the scaling law would indicate. Overpressure data recorded by Hanna and Zabetakis are presented in Figure 1 as a plot of overpressure versus scaled distance. The plot indicates that the overpressure decays as scaled distance to the -0.6 to -0.85 power [*1*]. This small negative slope indicates that the peak overpressure decayed very slowly with distance.

Another study of airblast overpressure from explosives was conducted in 1971 by Olson and Fletcher, who studied the propagation of blast waves produced by production blasts in an underground copper mine [*2*]. The authors found that for both dynamite and AN-FO blasts, the peak overpressure could be expressed as the equation

$$P = 4.9 \times 10^3 \, (D/W^{1/3})^{-2.15},$$

where D is the distance from the blast and W is the weight of explosive. Here the slope of the log-log overpressure versus scaled distance plot is much more negative than that observed by Hanna and Zabetakis (see Figure 2), indicating that the peak overpressure fell off much faster with scaled distance.

In 1980 Systems, Science, and Software conducted a study of blast wave propagation in mines under contract to the Bureau of Mines [*3*]. Laboratory studies of blast wave propagation in an array of pipes and instrumented explosive shots in two gold mines were conducted in an effort to determine how the blast wave is affected by the presence of crosscuts, side branches, splits in the entry, and narrowing and widening of the entry. The study was not directly intended to determine how the peak overpressure decayed with distance down the entry, but analysis of the results for shots in a gold mine indicates that peak overpressure decays approximately as distance to the -0.9 power; the section of the mine employed for the study contained no crosscuts but there were a couple sharp corners and variations in mine dimensions of a foot or two. This result is in reasonable agreement with the work of Hanna and Zabetakis.

The current study was conducted in an effort to better understand how explosive blast waves propagate in underground mines. Blast waves in underground mines travel much further than is the case in open air and a better understanding of their behavior will contribute to safer blasting.

LAKE LYNN LABORATORY

The Bureau's Lake Lynn Laboratory 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 facilities. This state-of-the-art laboratory is located in the rural foothills of the Allegheny Mountains of Pennsylvania, approximately 60 miles southeast of Pittsburgh.

Lake Lynn Laboratory 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 (see Figure 3). It was built at an abandoned commercial limestone quarry, where underground entries 50 ft wide by 30 ft high were developed when surface mining ceased in the late 1960's. From these old workings, the Bureau developed a total of 7,500 ft of 20 ft wide by 6 ft high entries. These 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 simulate room-and-pillar and longwall configurations.

EXPERIMENTAL

Tests were conducted in the room-and-pillar part of the simulated coal mine at Lake Lynn Laboratory. Explosives were detonated at two locations: the dead-end of A-drift and the intersection of A- and E-drifts. These locations were chosen because they both allowed us to observe propagation of the blast wave through the branching tunnels in the room-and-pillar section of the facility and also allowed us to observe the difference between a detonation in the dead end of a tunnel and at an intersection where the blast wave can propagate in three directions.

Two explosives, C4 and TNT, were employed in the research. We initially planned to employ TNT in all tests since there is extensive information available in the literature on the propagation of blast waves from TNT in surface detonations. Conducting the experiments using TNT proved to be a problem, however, because we were unable to cast TNT charges within the time frame available for the research and we felt that shooting packages of flaked TNT might not yield reproducible results. We therefore decided to substitute C4 for TNT. C4 yields a higher peak pressure than TNT so the weight of C4 that yields a peak pressure equivalent to a given weight of TNT was determined based on the relationship that peak pressure is proportional to heat of detonation [4]. The heat of detonation for C4 is 1.40 kcal/g and the heat of detonation for TNT is 1.02 kcal/g, yielding a ratio of $1.02/1.40=0.72$ [5]. Thus, 3.6 lb of C4 was substituted for 5 lb of TNT, 7.2 lb of C4 was substituted for 10 lb of TNT, etc. In practice we found that the flaked TNT yielded reproducible results and used it in some of the shots.

A number of explosive shots were also conducted in the surface quarry area of Lake Lynn Laboratory to serve as a comparison to the results of the underground shots. The surface and underground tests are summarized in Table 1.

INSTRUMENTATION

Pressure pulses were recorded using PCB Piezotronic[1] Model 102A04 pressure transducers having a range of 0-1000 psi with a rise time of 1 microsecond (resonant frequency 500kHz), and strain-gauge type pressure transducers permanently mounted in the underground facilities for the study of gas explosions. The strain gauge type pressure transducers were Genisco Model SP500 (now Patriot Sensors) and Dynisco Model APT380DV-1C-C29. The location and identification of the PCB Piezotronic pressure transducers are illustrated in Figure 4 for the shots at the face of A-drift. The setup for the shots at the intersection of A- and E-drifts was similar with the exception that P1 was placed 46 feet from the face and P2 was placed 5 feet closer to the face, i.e., 5 feet from the shot. The Genisco and Dynisco transducers were connected to the computer room in the surface control building where the data was digitized and stored. The PCB Piezotronic pressure transducers were connected to data collection instrumentation and a computer in the instrumentation room. The slow response time of the Genisco and Dynisco pressure transducers (in the range of 0.2 to 0.5 ms) and the 1500 samples/sec rate were too slow to be useful in measuring overpressure but they still yielded useful information on blast wave arrival times.

RESULTS

Figures 5 through 8 illustrate the peak overpressures recorded by the PCB Piezotronic pressure transducers for the four underground shots. The transducers closest to the detonation, P1 (46 ft) and P2 (105 ft), recorded initial pressure pulses that were narrow and well defined (<1 ms width). Some character is present in the traces as the transducers detect pressure pulses reflected by the roof and rib. Further from the detonation at P5 (205 ft) and P8 (305 ft) the pressure pulses broaden.

The pressures recorded by transducer P3 in the shots at the face of A-drift are difficult to explain; the trace appears to be an overlap of two relatively strong pulses spaced 4-5 ms apart. Where the two pulses could be coming from is not clear. A time difference of 4 ms at P3 represents a difference in travel time of about 6 feet. There do not appear to be two paths to P3 that differ by 6 feet. In addition, if the multiple pulses detected by P3 were real, why didn't they show up at P4? Lacking a good explanation for the multiple pulses at P3, we must consider the possibility that they might be artifacts of the transducer and its mount, possibly vibrations of a loose transducer.

Transducers P6 and P7 also appear to be detecting multiple pressure pulses spaced close together in time. In these cases the origin of the multiple pulses is easier to explain. Between the detonation and transducers P6 and P7 there are multiple paths that differ by only a few feet in travel distance, with corresponding time displacements of several ms. Pressure pulses will

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[1]Reference to specific brand names is made for identification only and does not imply endorsement by the U.S. Bureau of Mines.

be arriving at P6 and P7 with time shifts on the order of milliseconds leading to relatively complex wave shapes.

Data from the underground and surface shots (Figures 9 and 10) were studied to determine how the peak overpressure decreases with distance. To properly conduct this analysis in an underground entry, data should have been collected for a straight section with no crosscuts. This was not done here because we were originally hoping to determine the effect of crosscuts on pressure decay. The data does, however, allow us to evaluate the distance effect if we look only at transducer data that is in direct line of sight of the detonation and we assume that the presence of crosscuts do not have a significant affect on the peak overpressure. This assumption may not be too far off since Peterson, et. al. showed that peak overpressure decreased by only about 10% on passing a side tunnel [3].

Figure 11 illustrates a log-log plot of peak overpressure versus scaled distance for the four underground shots. Carrying out a regression analysis to fit a straight line to the data yields a straight line with a slope of -0.85. For comparison, Figure 12 is a log-log plot of peak overpressure versus scaled distance for the two shots in the surface quarry. For the surface shots the data is fit by a straight line with a slope of -1.65.

As mentioned above, the data from the strain gauge type transducers permanently mounted in the entries were considered to be too slow to give valid data on the peak overpressures. These transducers did, however, yield valid data on the arrival time of the overpressure pulse. An attempt was made to determine the peak overpressures down A-, B-, and C-drifts from the arrival times using a technique detailed by Kinney [6]. Figure 13 illustrates this type of analysis for Shot 4, detonation of 28.8 lb of C4 at the face of A-drift. For comparison, the data from the PCB Piezotronic transducers is included, as well as lines through the P1 transducer with slopes of -0.9 and -1. The peak overpressures deduced from the arrival times agree with the data from the PCB Piezotronic transducers reasonably well at shorter distances and seem to follow a slope in the neighborhood of -0.9. At longer distances the agreement does not hold and the slope appears to become increasingly more negative. This behavior could be an effect of the crosscuts or a change in the mechanism for peak overpressure decay with distance; the explanation for this behavior is unknown at this time. This analysis was conducted in the expectation that it would yield information on the effect of path geometry on peak overpressure; the pressure pulse traveled directly down A-drift, but had to go around two corners to travel down B- and C-drifts. We would have expected that for a given distance, the pressure for A-drift would be higher than those for B- or C-drift; this is not the case. The pressures in A- and B-drift are about the same while those in C-drift were significantly higher.

CONCLUSIONS

Peak overpressure from an explosive blast decays much more slowly with distance underground than is the case on the surface. In a typical underground entry the peak overpressure decays proportional to distance to the -0.9 power. Data collected in the present study was insufficient to determine the effect of crosscuts but Peterson, et.al [3] found that the peak pressure after a side tunnel was 90 pct of that before the crosscut, i.e. the crosscut causes a 10 pct loss of peak pressure.

In underground blasting it is typical for a blaster to get around at least one corner to protect himself from the blast. This practice provides protection from flyrock but provides little protection from airblast. In normal shooting there is no significant airblast since the explosives are confined in boreholes, but airblast may become significant in cases of blown out holes, accidental initiation of explosives, or unconfined blasting; in these cases precautions to protect personnel from airblast must be taken.

REFERENCES

1. Hanna, N.E. and M.G. Zabetakis, Pressure Pulses Produced by Underground Blasts, Bureau of Mines Report of Investigation 7147, 1968.

2. Olson, J.J. and L.R. Fletcher, Airblast-Overpressure Levels from Confined Underground Production Blasts, Bureau of Mines Report of Investigation 7574, 1971.

3. Peterson, C.F., J.R. Barthel, and S. Peyton, Blast Wave Propagation in Mines, Bureau of Mines Contract No. JO199003, Final Report, December 19, 1980.

4. Engineering Design Handbook, Principles of Explosive Behavior, AMC Pamphlet AMCP 706-180, Headquarters, U.S. Army Material Command, April, 1972, p. 3-5.

5. Dobratz, B.M. and P.C. Crawford, LLNL Explosives Handbook: Properties of Chemical Explosives and Explosive Simulants, Lawrence Livermore National Laboratory, Livermore, CA, January 31, 1985.

6. Kinney, G.F., Explosive Shocks in Air, The MacMillan Company, New York, 1962, Example 5.2, pp 85-86.

Table 1. Test summary

Shot Number	Shot Location	Explosive	Comments
1	End of A-Drift	7.2 lb C4	Equivalent to 10 lb of TNT
2	End of A-Drift	14.4 lb C4	Equivalent to 20 lb of TNT
3	End of A-Drift	28.8 lb C4	Equivalent to 40 lb of TNT
4	Intersection[1]	14.4 lb C4	Equivalent to 20 lb of TNT
5	Surface Quarry	10 lb TNT	
6	Surface Quarry	7.2 lb C4	Equivalent to 10 lb of TNT

[1]Intersection of A- and E-drifts

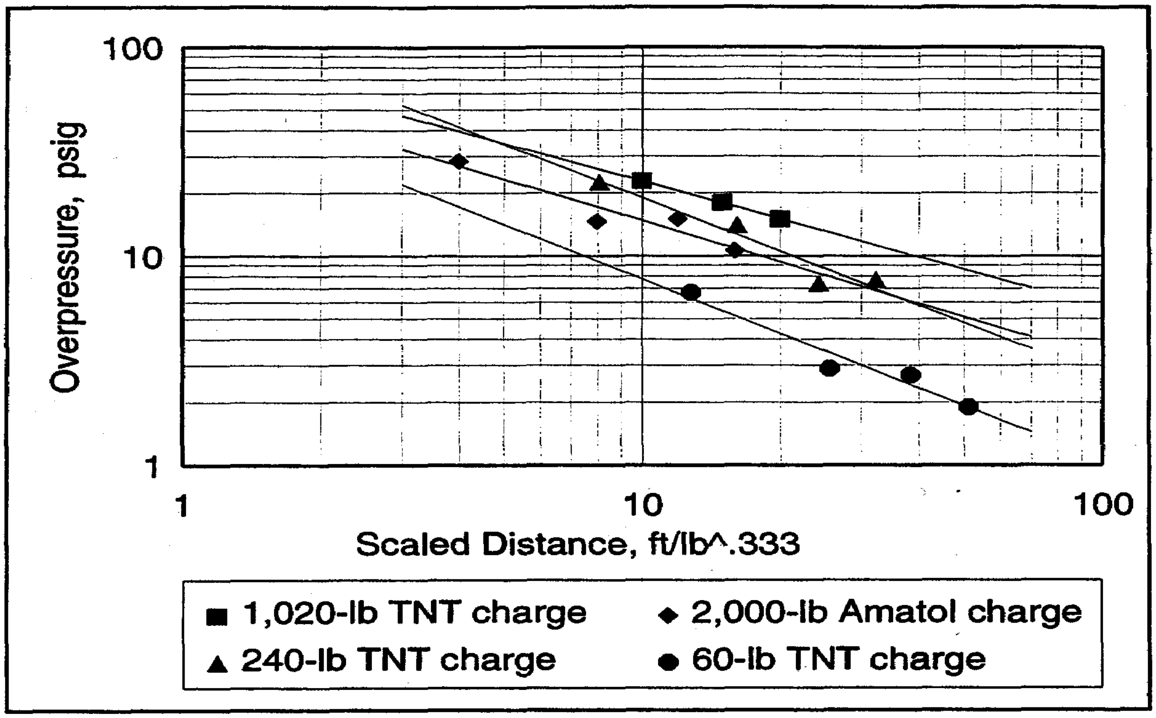

Figure 1. Data of Hanna and Zabetakis from shots in an abandoned underground limestone mine. (Ref. 1)

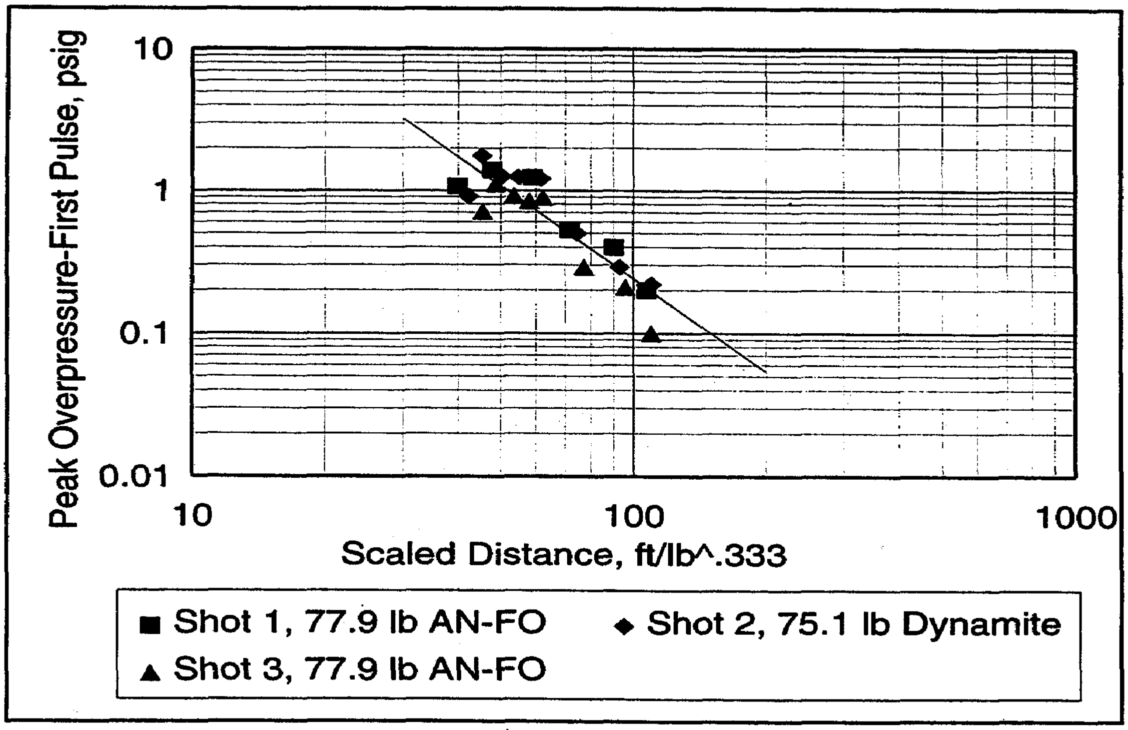

Figure 2. Data of Olson and Fletcher from shots in an underground copper mine. (Ref. 2)

PLAN VIEW OF UNDERGROUND MINE WORKINGS

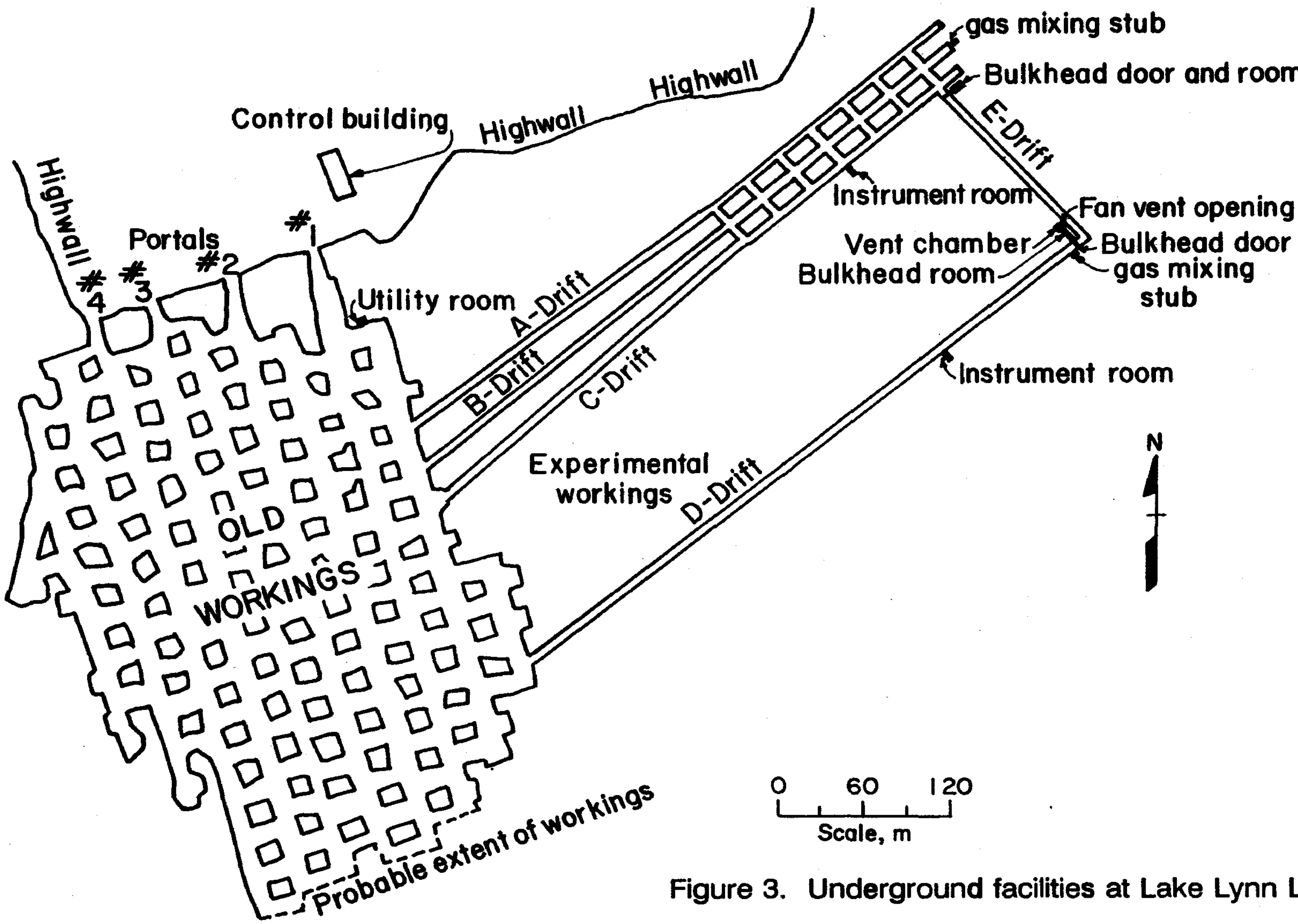

Figure 3. Underground facilities at Lake Lynn Laboratory.

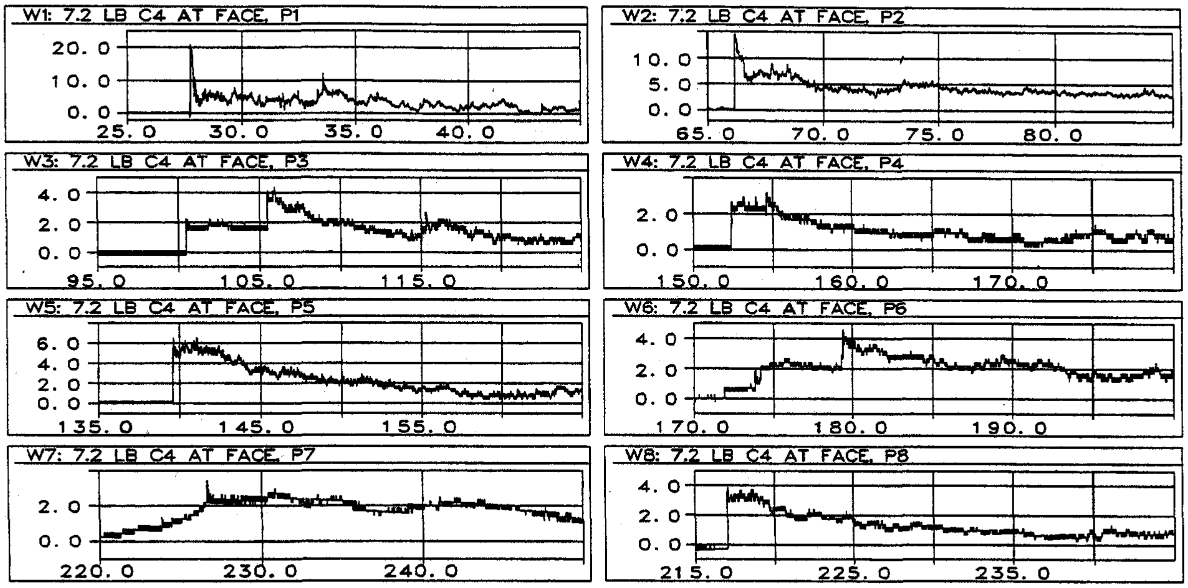

Figure 5. Overpressure recorded by the 8 PCB Piezotronic pressure transducers for the shot of 7.2 lb of C4 explosive at the face of A-drift. (Absissa is ms and ordinate is psig).

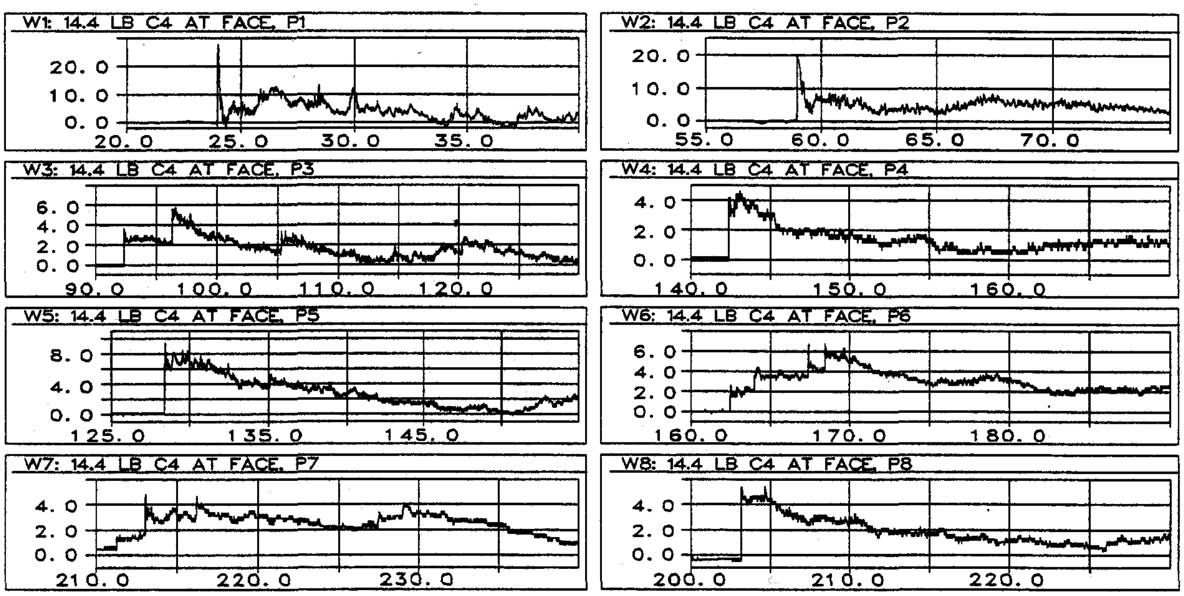

Figure 6. Overpressure recorded by the 8 PCB Piezotronic pressure transducers for the shot of 14.4 lb of C4 explosive at the face of A-drift. Absissa is ms and ordinate is psig.)

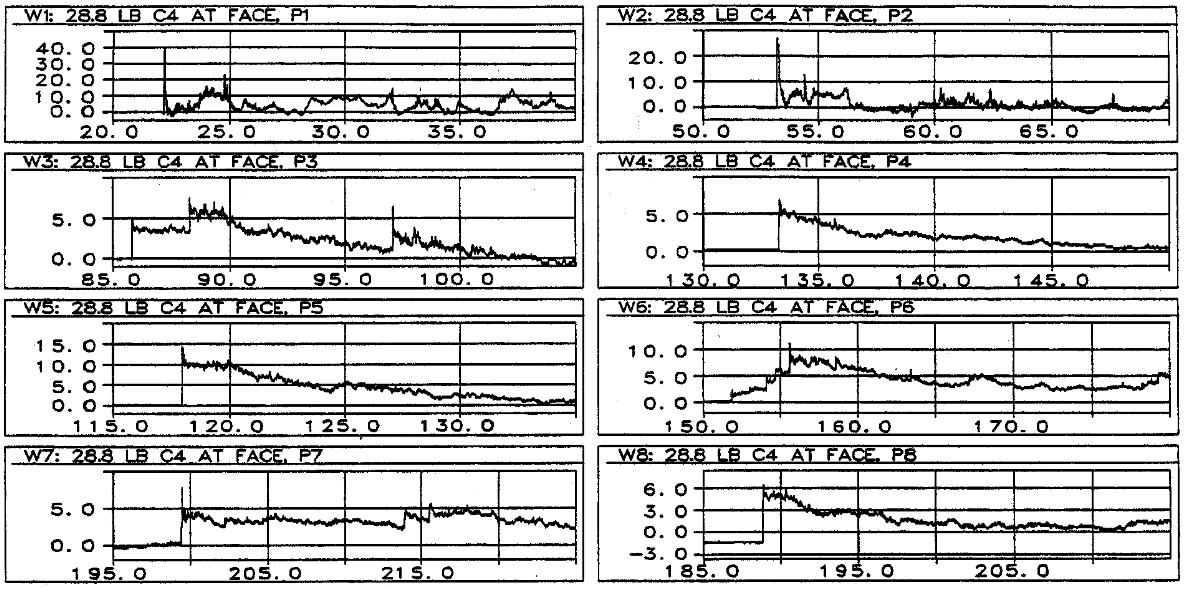

Figure 7. Overpressure recorded by the 8 PCB Piezotronic pressure transducers for the shot of 28.8 lb of C4 explosive at the face of A-drift. (Absissa is ms and ordinate is psig).

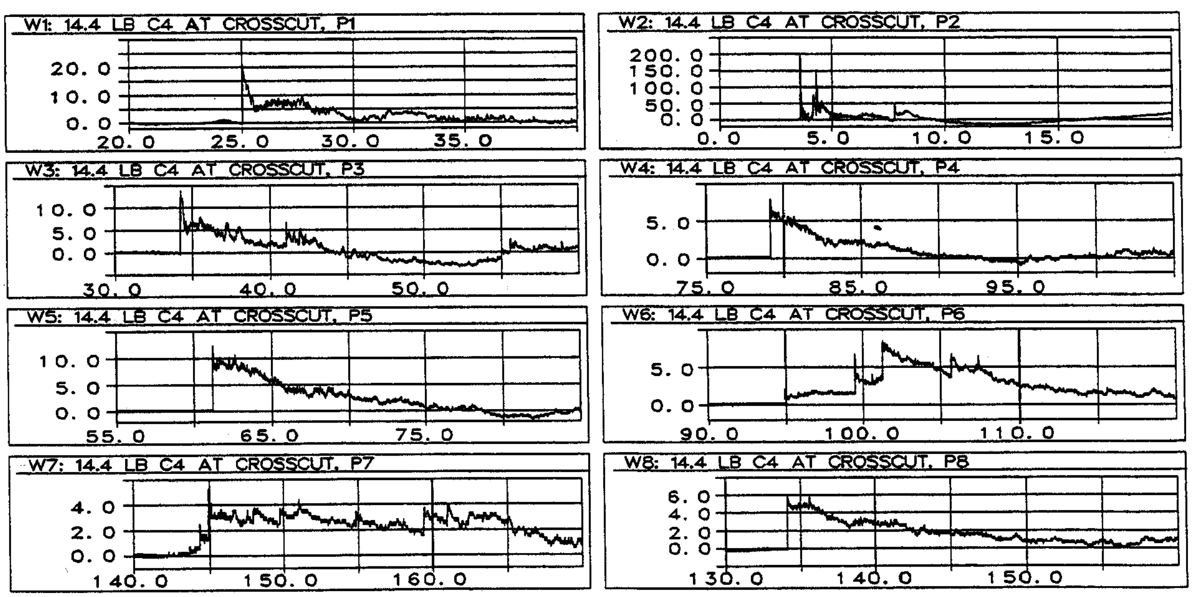

Figure 8. Overpressure recorded by the 8 PCB Piezotronic pressure transducers for the shot of 14.4 lb of C4 explosive at the intersection of A- and E-drifts. (Absissa is ms and ordinate is psig.)

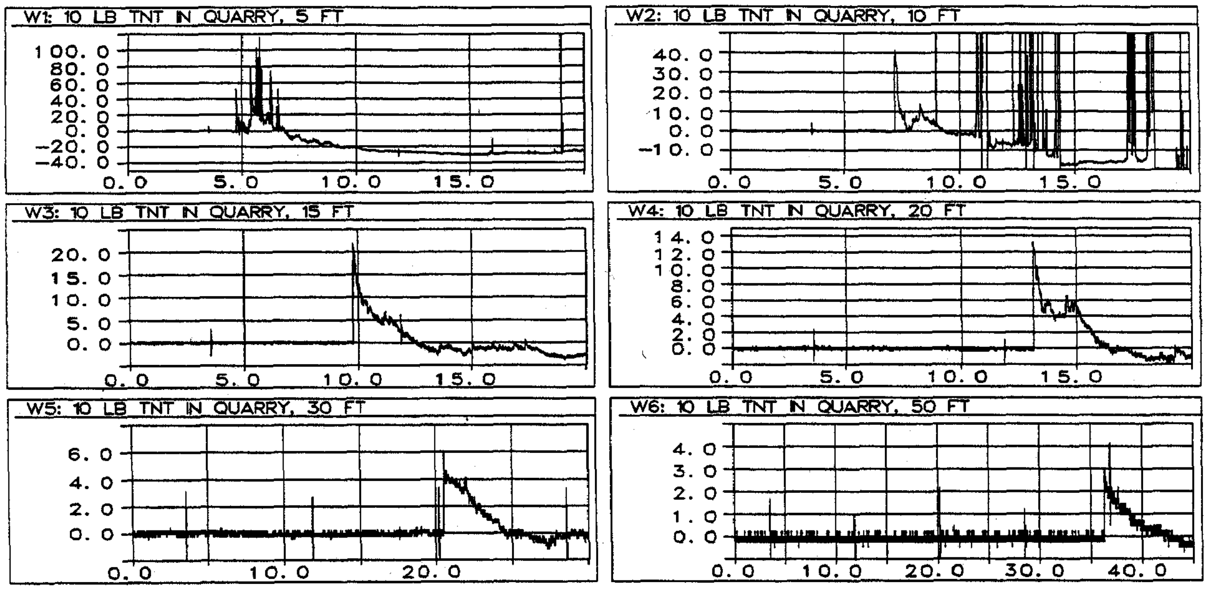

Figure 9. Overpressure recorded by the 6 PCB Piezotronic pressure transducers for the shot of 10 lb of TNT in the surface quarry. (Absissa is ms and ordinate is psig).

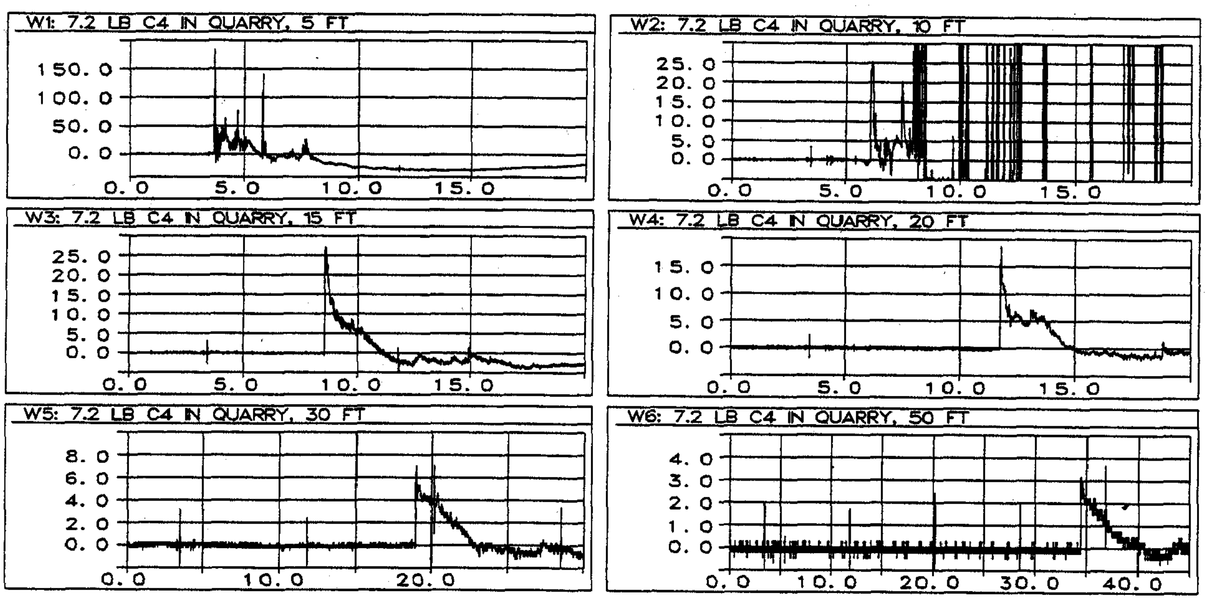

Figure 10. Overpressure recorded by the 6 PCB Piezotronic pressure transducers for the shot of 7.2 lb of C4 explosive in the surface quarry. (Absissa is ms and ordinate is psig.)

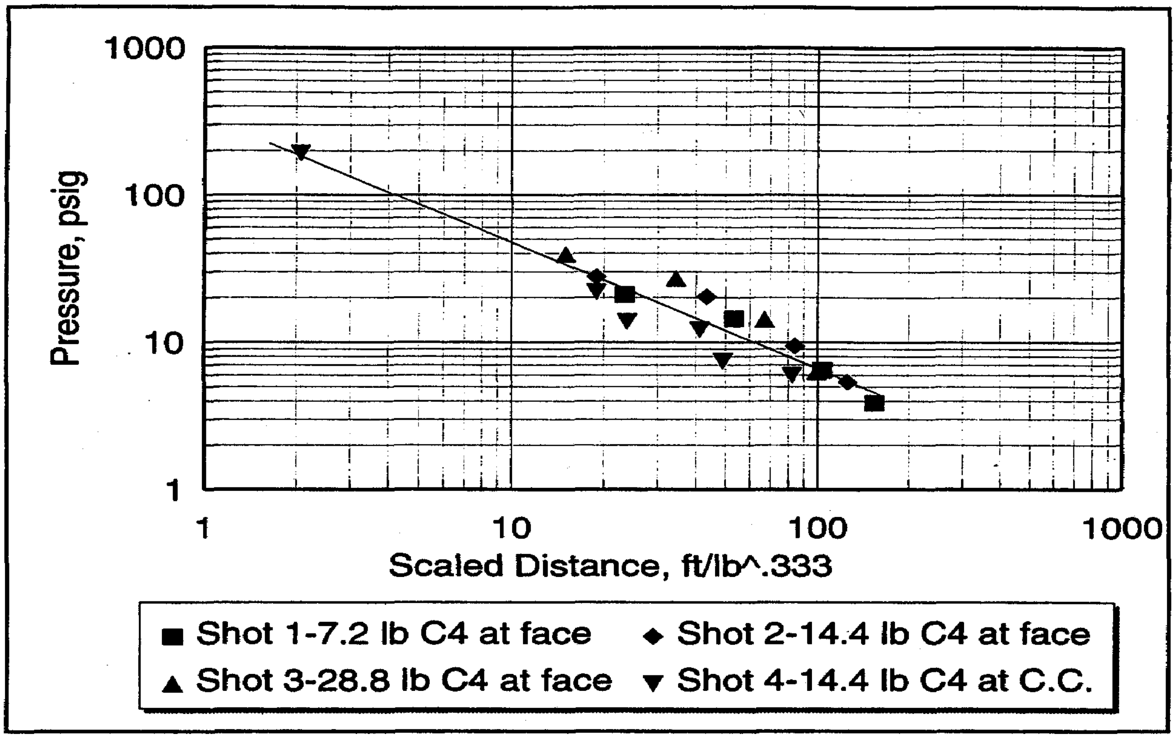

Figure 11. Plot of overpressure versus scaled distance (distance/explosive weight $^{1/3}$) for the underground shots.

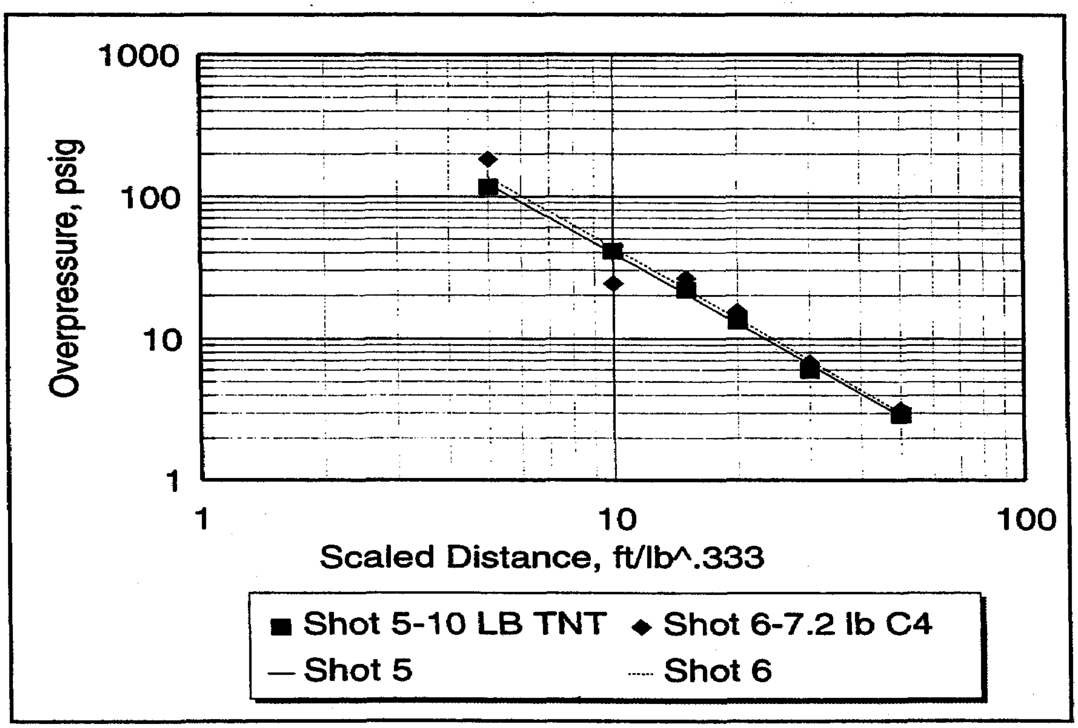

Figure 12. Plot of overpressure versus scaled distance for the surface shots.

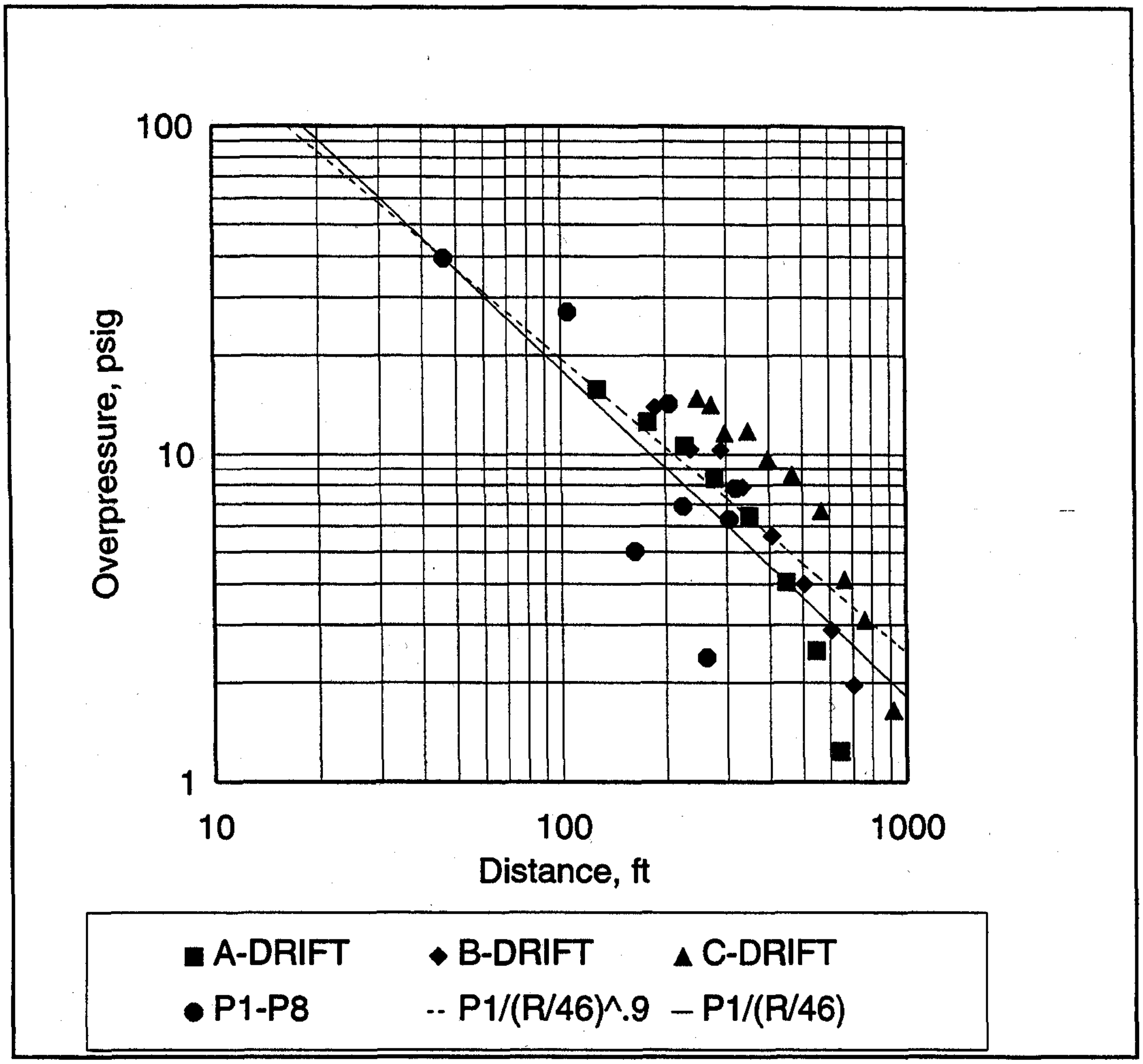

Figure 13. Overpressures for the shot of 28.8 lb of C4 at the face of A-drift as determined from time of arrival.