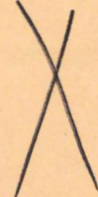


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**Airblast-Overpressure Levels
From Confined Underground
Production Blasts**



UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 7574

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From Confined Underground
Production Blasts**

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**UNITED STATES DEPARTMENT OF THE INTERIOR
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AIRBLAST-OVERPRESSURE LEVELS FROM CONFINED UNDERGROUND PRODUCTION BLASTS

by

James J. Olson¹ and Larry R. Fletcher²

ABSTRACT

The Bureau of Mines recorded and analyzed overpressure levels for three production blasts at the White Pine copper mine, Upper Michigan, to obtain representative data from single-heading blasts in a long, straight haulageway and to estimate the damage potential inherent in production blasts fired in close proximity to underground structures. Commercial pressure gages with a flat response to 1 kHz were used with an FM tape recorder to record the overpressures from one dynamite and two AN-FO (ammonium nitrate-fuel oil), 500-msec production blasts having zero-delay charge weights of about 75 lb (34 kg).

The recorded waveforms from the underground blasts (1) were more complex than the typical free-air wave, (2) were of longer duration, and (3) had numerous secondary arrivals due to reflections from the ribs and roof. The waveforms showed that the zero-delay charges produced the only high overpressures. First pulse peak overpressures from the blasts ranged from 0.10 lb/in² (6.9×10^2 N/m²) at a distance of 471.1 ft (144 m) to a maximum of 1.76 lb/in² (121.3×10^2 N/m²) at 191.7 ft (58.4 m) from the blasts. An analysis of variance of the first pulse overpressures from the three White Pine blasts showed that no statistically significant difference existed among the overpressure levels from the dynamite and AN-FO blasts and that a single equation

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

where P = overpressure in pounds/inch²,

D = distance from the blast in feet,

and W = zero-delay charge weight in pounds,

could be used to describe the falloff of overpressure with distance.

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INTRODUCTION

Through its in-house research programs, the Bureau of Mines has always had an active interest in both the economic and safety problems associated with explosive fragmentation of rock. The ability to predict behavior of blast waves in an underground excavation will help promote safer working environments for miners. During the past several years, the Bureau has conducted extensive field and theoretical studies to develop criteria to prevent structural damage from ground vibrations generated by quarry blasting (1, 9-10).³ The Bureau has also studied problems involving the measurement of airblast overpressures generated by various modes of surface blasting and has worked toward reducing the damage potential of airblast to nearby surface structures (3, 6, 21-22).

Because of the ever-increasing use of explosives in tunnel excavation under urban areas, the Bureau has extended the study of ground vibrations to include underground mine blasts to determine whether factors used to design safe quarry blasts can also be used to design underground mine blasts having nondamaging vibration levels (2, 11-13).

This airblast study conducted at White Pine represents part of the overall program in explosive fragmentation conducted by the Bureau in underground mines. The experiment was conducted in a room and pillar mine, a mining environment typical of many operations in the United States. The overpressures were recorded from routine production blasts drilled and fired in the same manner as any other blasts in the mine. Special care, however, was taken in loading the shotholes to insure that the proper weight of explosive charge was used for each delay period.

Although much research has been conducted on overpressures from confined and unconfined blasts on the surface by centers such as The Ballistic Research Laboratories, Aberdeen Proving Ground, Md.; and Stanford Research Institute, Menlo Park, Calif. (15, 17), very little work has been done on blasts in underground excavations. Bureau researchers Hanna and Zabetakis (4) conducted experiments in the large openings of an abandoned underground limestone mine to study the behavior of blast waves reflected from mine surfaces. They made four tests with unconfined TNT and modified amatol charges ranging in weight from 60 to 2,000 lb (27 to 907 kg)⁴

³Underlined numbers in parentheses refer to items in the list of references at the end of this report.

⁴The prime units in the text, tables, and illustrations of this publication are the U.S. customary units. The approximate equivalents in the International System of Units (SI) are included in accordance with the rules for introducing modernized metric units established by the National Bureau of Standards ASTM Metric Practice Guide, Handbook 102. In accordance with the SI convention, a space rather than a comma is used to separate the digits in a metric number such as 15 000. The U.S. customary numbers used throughout the report include commas, where necessary, to separate the digits. The period is used as a decimal point in both SI and U.S. customary numbers.

Abbreviations

U.S. customary units	SI units
in = inch	mm = millimeter
ft = foot	m = meter
lb = pound	kg = kilogram
mv = millivolt	N = newton
msec = millisecond	mv = millivolt
Hz = Hertz (unit of frequency--cycle/second)	msec = millisecond
	Hz = Hertz (unit of frequency--cycle/second)

and found Sachs' cube-root scaling law for peak pressures to be valid only within about one tunnel diameter. At greater distances, the pressures obtained along direct paths were generally higher than this surface blast scaling law would indicate.

ACKNOWLEDGMENTS

The authors wish to acknowledge the generous cooperation of the White Pine Copper Co., White Pine, Mich. Through his assistance in site selection and scheduling, Jack Parker, director of the Rock Mechanics Research Department at White Pine, made a significant contribution to the success of the field experiment. The authors also wish to acknowledge the assistance of Dr. Arlo D. Hendrickson, mathematician, formerly with the Twin Cities Mining Research Center, who performed the statistical analysis in this report.

TEST SITE

The experiment was conducted in one of the experimental development headings of the White Pine copper mine at White Pine, Mich. The White Pine townsite and mine are very close together and are located in Ontonagon County between the Porcupine Mountains and the Bergland Hills (fig. 1).

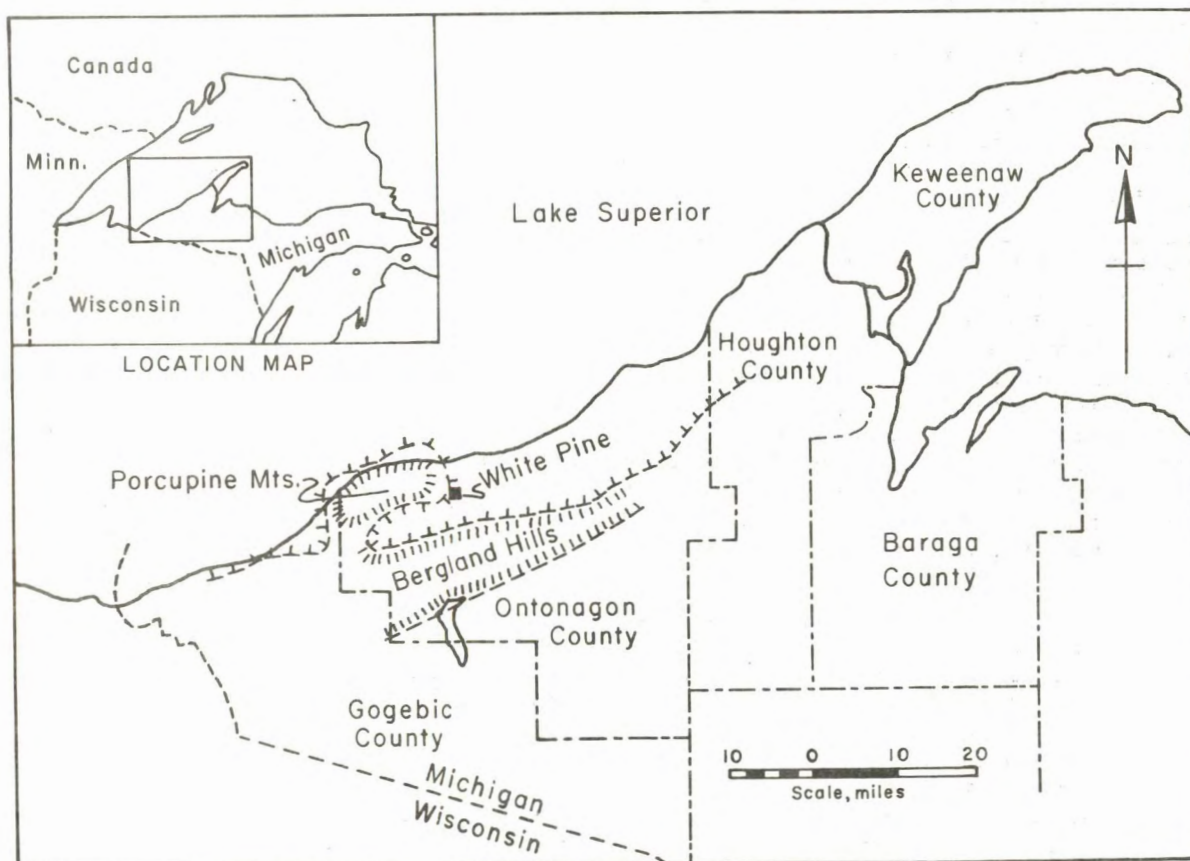


FIGURE 1. - Location of White Pine Townsite and Mine (14).

The general features and modes of operation of the mine have been described in an earlier Bureau publication (11) and also by Parker (14). The White Pine ore body has been described by White and Wright (20), who identified the copper-bearing beds as the Nonesuch Shale and the Copper Harbor Conglomerate. The most valuable mineralized zones comprise about 15 ft (approx. 4.6 m) of strata (lower sandstone, parting shale, upper sandstone, and upper shale) near the contact between the Nonesuch Shale and Copper Harbor Formations.

Because previous workers (4) had shown that geometrical parameters could strongly influence overpressure levels in an underground mine, every attempt was made to find a test heading with relatively simple geometric configurations (such as a long, straight, heading with few crosscut drifts). Several areas of the mine were examined before the mine haulage-way (heading LH-1) shown in figure 2 was selected. Although the configuration of LH-1 was not ideal, the overall aspects of the working area provided the best compromise of desirable features compatible with the company's mining schedule.

The openings in the immediate area of LH-1 were confined to the parting-shale zone and ranged from 8 ft (approx. 2.4 m) to 9 ft (approx. 2.7 m) in height. Excavated openings just outside the test heading area (near gage station 8) were full column headings encompassing the parting shale, the upper sandstone, and a small portion of the upper shale. These headings were approximately 15 ft (approx. 4.6 m) high.

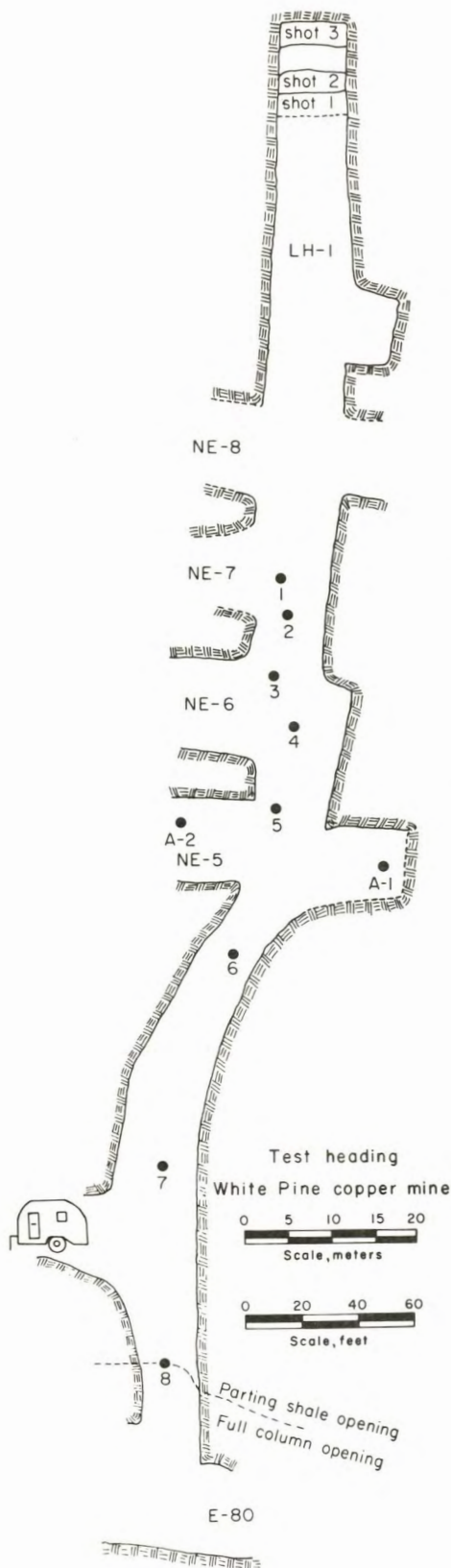


FIGURE 2. - Map of the White Pine Test Heading Showing Gage and Shot Locations.

EXPERIMENTAL PROCEDURE

Instrumentation

The total instrumentation system used by the Bureau of Mines has been described in a previous report on roof vibrations from blasting (11).

In this experiment, piezoelectric blast pressure gages were installed at 10 locations in or near the haulageway (LH-1) to measure airblast overpressures. Gage stations 1 through 8 were positioned in an approximately linear logarithmic array down the center of the haulageway (fig. 2). Gage stations A-1 and A-2 were located in the crosscut drift NE-5 to provide information on pressure levels in areas slightly removed from the direct travel path down the heading.

The blast pressure gages were watertight and had an operating temperature range from -40° F (-40° C) to 212° F (100° C). Resonant frequencies for the gages were greater than 67 kHz and the overall frequency response for this type of gage was essentially flat up to 1 kHz. The nominal charge sensitivity for the gages was $3,000 \times 10^{-12}$ coulombs/lb/in² (approx. 0.44×10^{-12} coulombs/N/m²).

The pencil-shaped gages were alined along the axis of the haulageway and pointed toward the blast locations (fig. 3). Manufacturers' specifications stated that the gage alinement could vary up to 25° without seriously affecting the response (± 2 percent) of the gage to an oncoming pressure front.

Low noise instrument cables from each pressure gage were first joined to a patch box and then connected to a multiconductor cable. The extra length of multiconductor cable allowed the investigators to coordinate blasting operations from the instrument trailer, which was located in a safe position to the side of the haulageway.

Charge amplifiers (flat frequency response from 2 to 20 000 Hz ± 5 percent) were used to amplify the signals from the blast gages. The amplified outputs from the charge amplifiers were recorded on a 14-channel FM magnetic tape recorder at a speed of 60 in/sec (approx. 1 524 mm/sec) and replayed at a speed of 1-7/8 in/sec (approx. 47.6 mm/sec) to either an oscilloscope or a direct-writing oscillograph. Because of the 32 to 1 ratio between record and playback speeds, standard performance galvanometers (undamped natural frequency = 3 700 Hz) could be used with the playback oscillograph.

Sensitivity values of the piezoelectric blast pressure gages were obtained from standard calibration curves provided by the manufacturer. Individual system components, such as the tape recorder and charge amplifiers, were calibrated in the laboratory before the field experiments. During the experiments in the mine, the data channels were calibrated by recording the charge amplifier's calibration signal just before each shot. When the records were analyzed, a comparison of the unknown amplitude of the recorded waveform and the recorded calibration signal, together with the associated gain settings, yielded the indicated blast overpressures in lb/in². The recorded overpressure values were also converted to approximate SI units (N/m²) for presentation in this report.

Shooting and Recording Procedures

The study was originally planned as an 8-shot, 2×2 factorial experiment to test the relative importance of two parameters (type of explosive charge and type of delay cap--25-msec versus 500-msec) on airblast overpressure levels. Because of extremely bad roof conditions in the experimental development unit, the study had to be terminated after only three blasts had been completed.

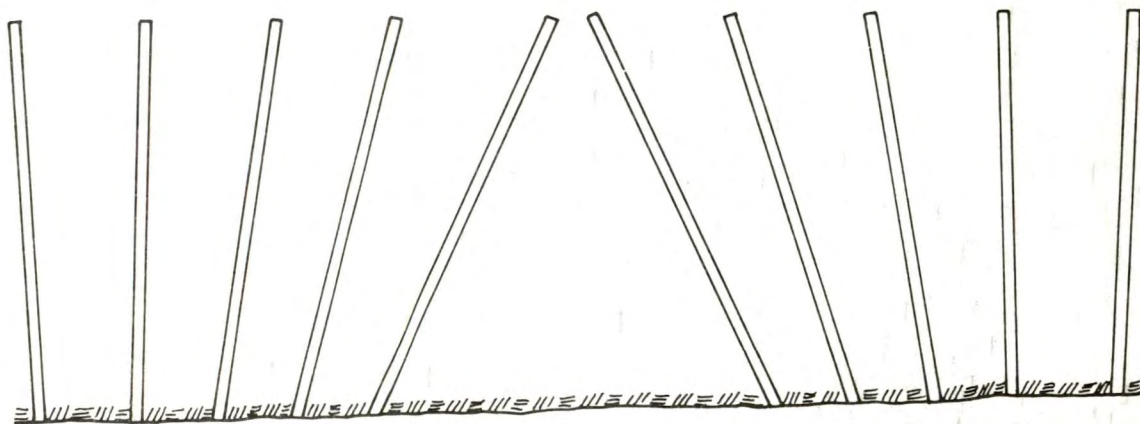
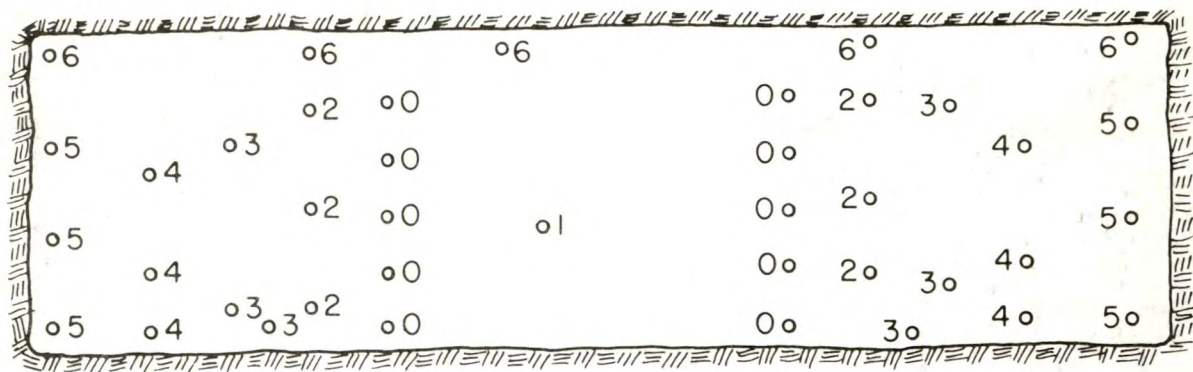


FIGURE 3. - Alinement of Blast Pressure Gage in Haulageway.

The production blast-round pattern used for the experiment in LH-1 is shown in figure 4. The shotholes were 1-5/8 in (41 mm) in diameter, and were all at least 10 ft (approx. 3 m) long. Three blasts recorded during the experiment were fired with 500-msec delay caps. No stemming materials were used in the shotholes.

Shots Nos. 1 and 3 were AN-FO blasts and were detonated with 75 percent⁵ ammonia gelatin primers weighing 0.45 lb (0.20 kg). The AN-FO prills were

⁵The percent strength of the cartridge explosives mentioned in this report (ammonia gelatin primers and ammonia dynamite) refers to the actual percentage by weight of nitroglycerin contained in the explosive.



Scale, feet



Scale, meters

Delay No.	Time interval sec
0	0.008
1	.5
2	1.0
3	1.5
4	2.0
5	2.5
6	3.0

FIGURE 4. - Blast Round Used in LH-1, Showing Delay Periods.

forced into the holes with a pneumatic loader. The total weight of explosive charge placed into each shothole was 7.79 lb (approx. 3.53 kg); hence, the explosive charge contained in the 10 holes fired with zero-delay caps totaled 77.9 lb (approx. 35.3 kg). Because fewer holes were used, the charge weights in portions of the blasts detonated with the larger delays were all substantially smaller than the zero-delay charge. The total charge weight detonated in the 40-hole AN-FO blasts was about 312 lb (approx. 141 kg).

Shot No. 2 contained 60 percent ammonia dynamite rather than AN-FO. The holes of shot No. 2 were loaded by inserting the primer into the hole followed by the rest of the cartridges. The loader then tamped the entire string of cartridges into place. Each shothole contained 7.51 lb (approx. 3.41 kg); hence, the charge weight of dynamite detonated by the zero-delay caps of shot No. 2 was 75.1 lb (approx. 34.1 kg). The total charge weight contained in the dynamite blast was 300 lb (approx. 136 kg).

The geometric configuration, gage positions, and location of the blasts were established by transit survey. The gage spread was positioned as close as possible to the blast area, but to prevent damage from flyrock, the closest practical approach was about 120 ft (approx. 36.6 m). While recording the blast overpressures, gages 1 through 3 were suspended only 2 ft (approx. 0.6 m) from the roof. Gages 4 through 8 were suspended about halfway between the roof and floor of the haulageway.

After the test rounds had been primed and loaded, a single shot line was strung from the blast area down LH-1 to the trailer where the recording operations were coordinated with the firing of the other production blasts in the area. The blast in LH-1 was detonated first and the overpressures recorded on tape. After the airblast from the shot in LH-1 had died out, the other blasts in the unit were fired from the remote shooting station located on the main route to the surface.

EXPERIMENTAL DATA

Kinney's comprehensive summary of the various phenomena associated with airblast (7) provides a convenient reference when dealing with problems of scaling blast pressures, calculating dynamic blast loads, and predicting structural response.

Kinney points out that blast waves, important aspects of any explosive detonation into air, are formed when the atmosphere surrounding the explosion zone is forcibly pushed back by the gaseous products of the explosion. The blast wave travels outward from the explosion and, because of the greater speeds of the higher pressure portions of the pulse, becomes an abrupt pressure discontinuity followed by negative- and positive-pressure phases.

Figure 5 shows a typical pressure-time curve recorded on the surface from an explosive detonated in free air. The gage at the remote location senses and records an immediate jump to a peak value of overpressure. The free-air overpressure condition is highly unstable and exhibits a rapid quasi-exponential decay.

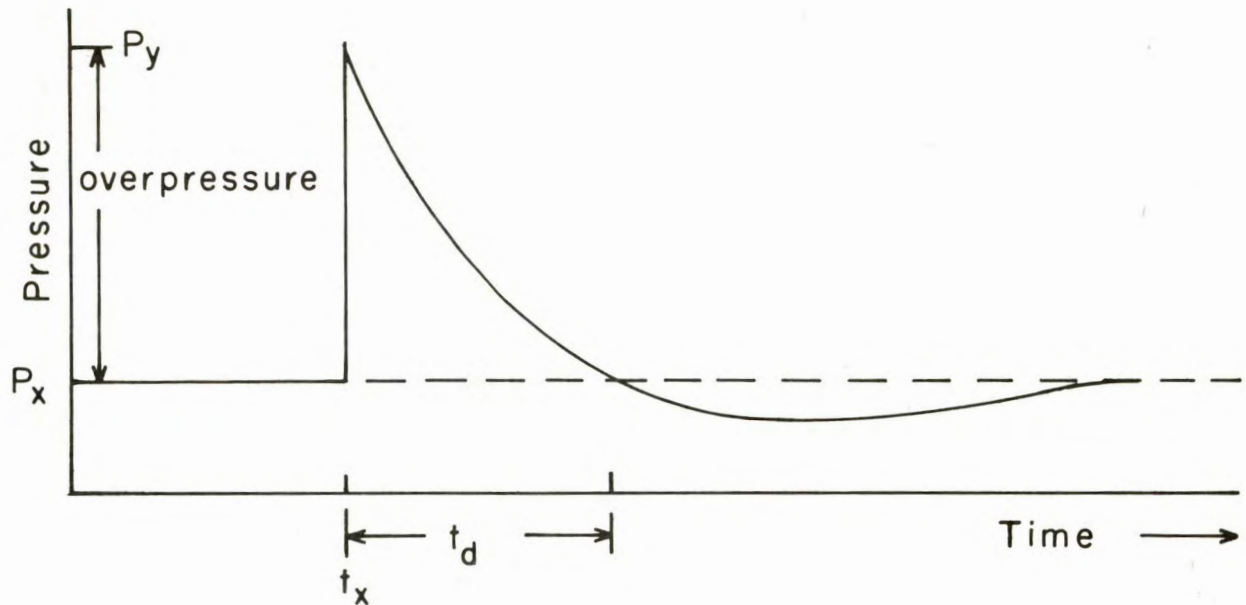


FIGURE 5. - Typical Pressure-Time Curve for an Explosive Blast Wave (7).

Because of the geometric configurations of the excavated headings, the overpressure records from underground mine blasts are more complicated than the free-air record of figure 5. The records may often display strong reflections from the pillars (ribs) and the roof or floor as well as the direct pulse transmitted from the blast zone through the air to the gage. From their study of large unconfined blasts in an underground limestone mine, Hanna and Zabetakis (4) found that the direct pulse waveforms corresponded with the free-air waveform for only a millisecond. The direct waveforms were then reinforced by a series of pulses from the floor, nearby objects, and surface irregularities. In many cases, Hanna and Zabetakis also found that the secondary arrivals (rib and roof reflections) were quite distinct and often had greater amplitudes than the direct pulses.

The overpressure records obtained from the three confined White Pine production blasts are shown in figures 6 through 8. The waveforms from the White Pine blasts also differed from the typical free-air waveform. The gage stations near the blast (1-5) had records that were most similar to the simple free-air waveform. The gage stations further down the drift (6 through 8, A-1, and A-2) produced records with numerous secondary arrivals. The direct or shortest direct-reflected path distances from the blast center to the gages were determined by triangulation. These distances are given both in feet and meters, and the peak amplitudes of each first pulse are given in lb/in^2 and N/m^2 .

First pulse peak overpressures for the AN-FO blasts ranged from 0.10 lb/in^2 ($6.9 \times 10^2 \text{ N/m}^2$) at a distance of 471.1 ft (144 m) for shot No. 3, to the maximum value 1.40 lb/in^2 ($96.5 \times 10^2 \text{ N/m}^2$) at 204.1 ft (62.2 m) obtained from shot No. 1. The peak overpressures for the dynamite blast (shot No. 2) ranged from 0.22 lb/in^2 ($15.2 \times 10^2 \text{ N/m}^2$) at a distance of 465.1 ft (142 m), to a maximum value of 1.76 lb/in^2 ($121.3 \times 10^2 \text{ N/m}^2$) at 191.7 ft (58.4 m) from the blast center.

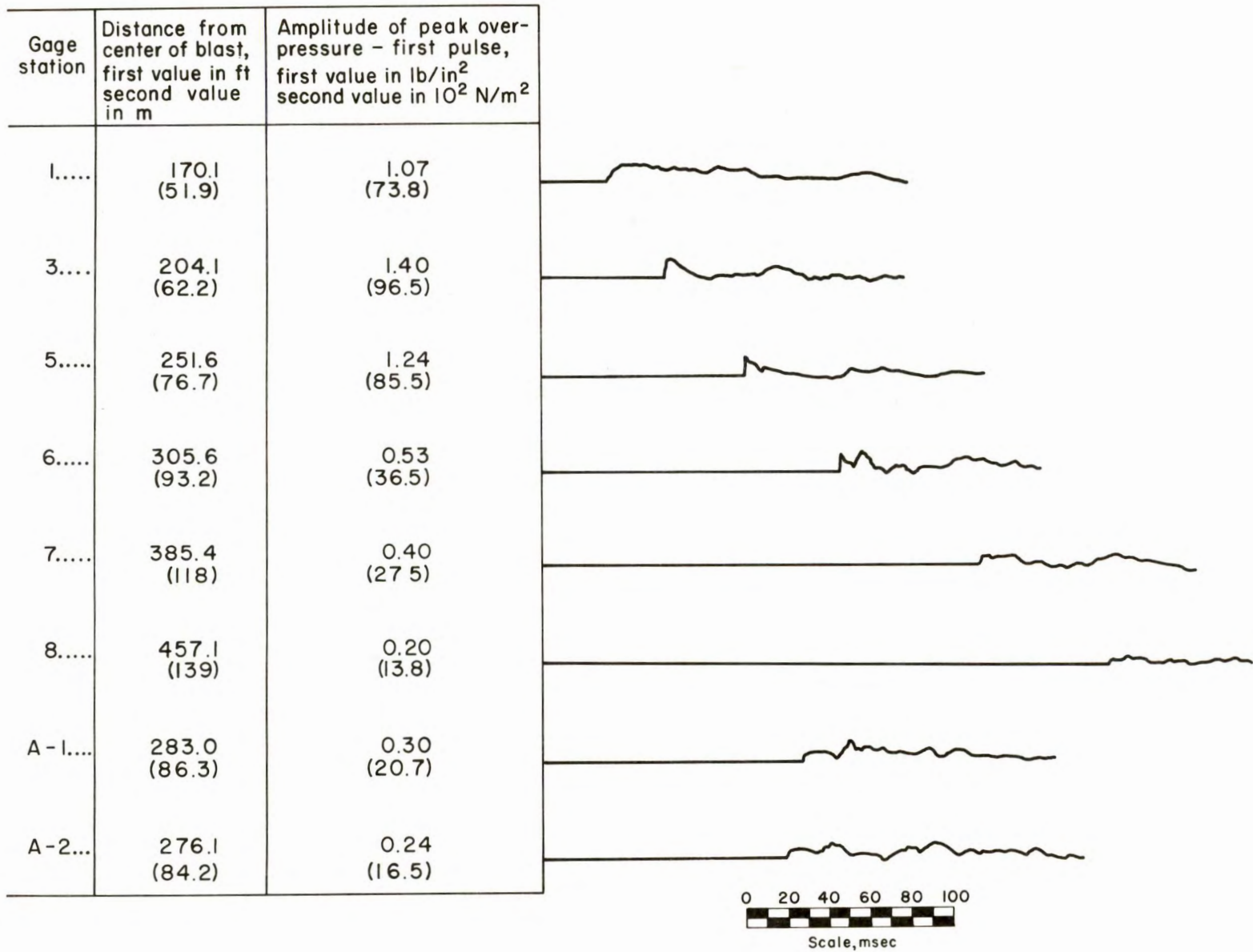


FIGURE 6. - Blast Overpressure Records From Shot No. 1 AN-FO (500 msec).

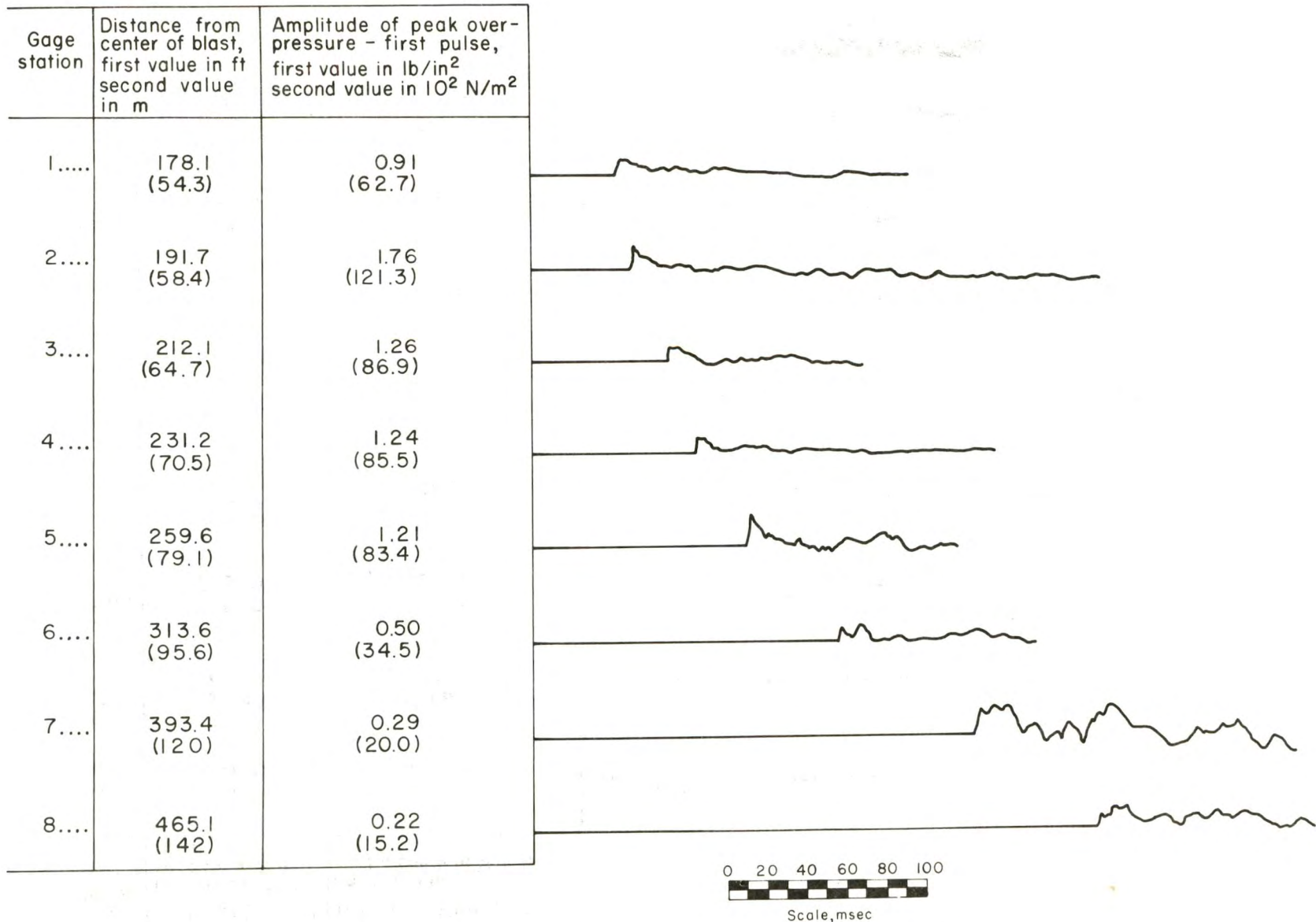


FIGURE 7. - Blast Overpressure Records From Shot No. 2 Dynamite (500 msec).

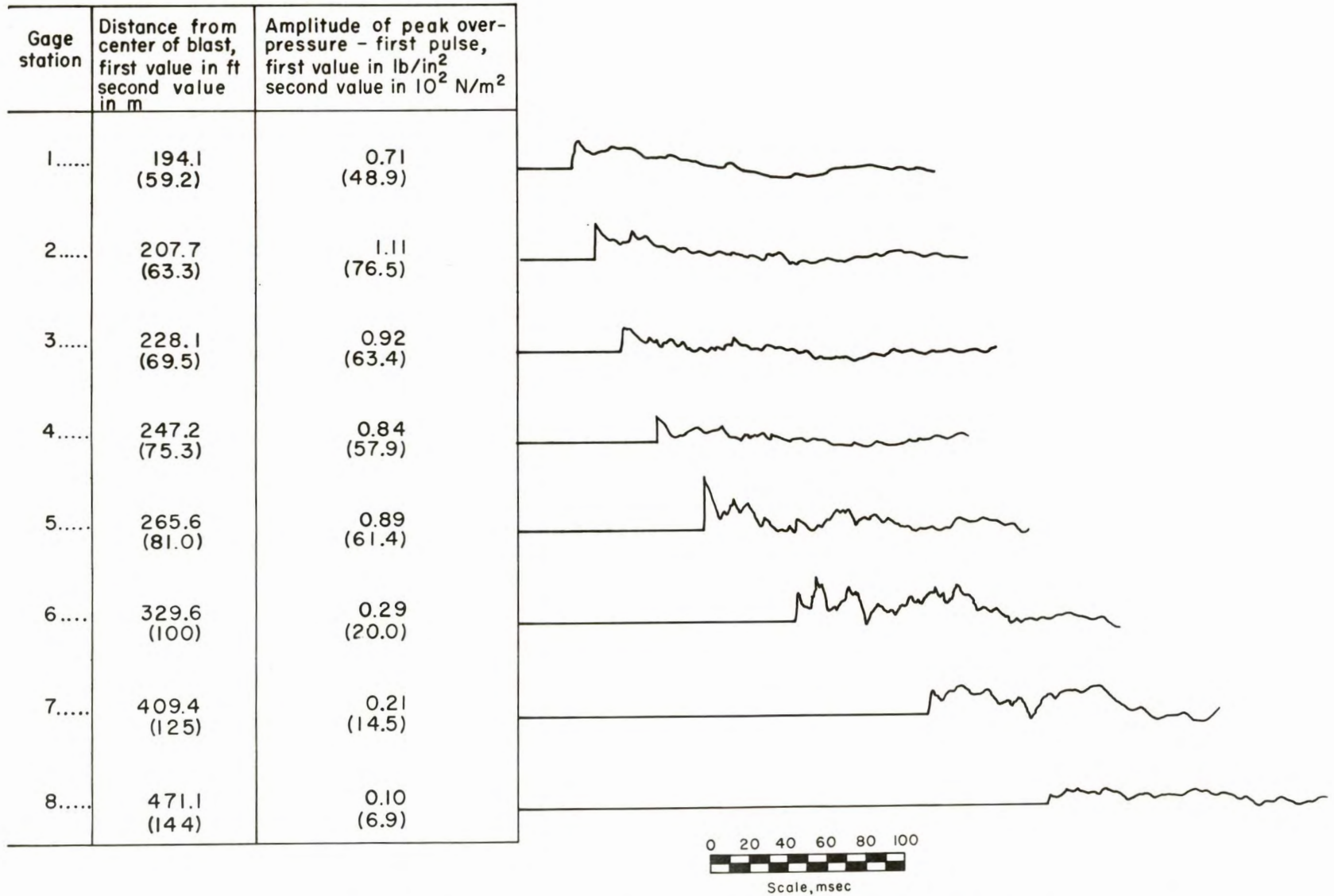


FIGURE 8. - Blast Overpressure Records From Shot No. 3 AN-FO (500 msec).

Because the nominal firing time of the second delay period of the slow delay blasts (No. 1, 500 msec) was far greater than the observed wave train lengths, the high amplitude signals present on the traces for about 100 msec after the arrival of the first pulse could only result from the direct wave produced by the zero-delay charge and possible reflections of this direct wave from the roof, ribs, and floor of the underground opening.

The No. 1 delay period detonated only one shothole. No arrivals near the nominal time interval for detonation of the caps could be observed on any of the traces, indicating that the overpressure levels were too low to be detected at the gain settings used to record the overpressures from the zero-delay charge.

The second largest charge of the round (six holes) was detonated with the next delay cap (No. 2, 1.0 sec), but no detectable overpressures were observed for this period either. In fact, all traces closely examined for events attributable to any of the later delay periods in the round were quiescent, and demonstrated that (1) the scatter in cap firing times spread out the airblast waves, and (2) the only high overpressures from the 500-msec-delay blasts resulted from the zero-delay charge.

Analysis of Data

Sachs' cube-root scaling law,

$$D_1/D_0 = (W_1/W_0)^{1/3}, \quad (1)$$

expressing the relationship between distance and the corresponding weight of explosive that produces a specified overpressure, is often used to predict overpressure levels from blasts in free air (17). From their study of unconfined blasts in large underground openings, Hanna and Zabetakis (4) found that the cube-root scaling law for peak pressures in free air was valid only in the near field (within about a tunnel diameter). Beyond the near field, pressures from direct arrivals were generally higher than the values predicted by the cube-root law, and in some cases, the pressures approached values obtained in the open when temperature inversions were encountered. Further study is necessary to determine whether an appropriate scaling factor and prediction relationships can be found for overpressures generated by production blasts in underground mines.

Because the data were insufficient to test for an appropriate scaling factor and since the overpressures from White Pine blasts were to be compared with data obtained in previous studies of surface blasts, cube-root scaling of the blast-to-gage distances was used to plot the data. A consistent pattern could not be observed among the secondary arrivals, and since most of the maximum overpressures were associated with the first pulse, only peak overpressure values of the first pulses are shown with the records in figures 6 through 8 and in the regression analysis (table 1). The distances, amplitudes, and scaled distances are given both in U.S. customary and SI units.

TABLE 1. - Peak-overpressure data used in regression analysis

Distance from blast, ft	Distance from blast, m	Amplitude of peak overpressure-first pulse, lb/in ²	Amplitude of peak overpressure-first pulse, 10 ² N/m ²	Scaled distance, ft/lb ^{1/3}	Scaled distance, m/kg ^{1/3}
SHOT NO. 1 AN-FO (500-MSEC DELAY); ZERO-DELAY CHARGE WT = 77.9 LB (APPROX. 35.3 KG)					
170.1	51.9	1.07	73.8	39.8	15.8
204.1	62.2	1.40	96.5	47.8	19.0
251.6	76.7	1.24	85.5	58.9	23.4
305.6	93.2	.53	36.5	71.6	28.4
385.4	118	.40	27.5	90.3	36.0
457.1	139	.20	13.8	107	42.4
SHOT NO. 2 DYNAMITE (500-MSEC DELAY); ZERO-DELAY CHARGE WT = 75.1 LB (APPROX. 34.1 KG)					
178.1	54.3	0.91	62.7	42.2	16.7
191.7	58.4	1.76	121.3	45.4	18.0
212.1	64.7	1.26	86.9	50.3	20.0
231.2	70.5	1.24	85.5	54.8	21.7
259.6	79.1	1.21	83.4	61.5	24.4
313.6	95.6	.50	34.5	74.3	29.5
393.4	120	.29	20.0	93.2	37.0
465.1	142	.22	15.2	110	43.5
SHOT NO. 3 AN-FO (500-MSEC DELAY); ZERO-DELAY CHARGE WT = 77.9 LB (APPROX. 35.3 KG)					
194.1	59.2	0.71	48.9	45.5	18.0
207.7	63.3	1.11	76.5	48.6	19.3
228.1	69.5	.92	63.4	53.4	21.2
247.2	75.3	.84	57.9	57.9	23.0
265.6	81.0	.89	61.4	62.2	24.7
329.6	100	.29	20.0	77.2	30.5
409.4	125	.21	14.5	95.9	38.1
471.1	144	.10	6.9	110	43.9

When the scaled data from the three blasts were plotted on log-log paper, an approximately linear falloff of overpressure with distance was observed. Accordingly, least-squares regression lines were fitted through each set of data to describe the attenuation (fig. 9). The vertical bar at the midpoint of each regression line represents one standard deviation of the scaled data above and below the regression line.

In the original 2 x 2 factorial experiment, analysis of variance tests were to be used to determine the relative importance of the type of explosive charge and the type of delay (25 msec or 500 msec) in producing airblast overpressures. Because the experiment had to be terminated without data from the 25-msec blasts, these tests could not be conducted. A simple analysis of variance, however, was performed to determine whether one regression line could be used to describe the attenuation with distance of the overpressure data from the three White Pine blasts (table 2). The results of the analysis on the data from these three shots showed no statistically significant difference between the overpressures produced by the two different types of explosive charge and that a single equation,

$$P = 4.9 \times 10^3 (D/W^{1/3})^{-2.15}, \quad (2)$$

where P = overpressure in pounds/inch²,

D = distance from the blast in feet,

and W = zero-delay charge weight in pounds,

could be used to describe the overpressure falloff with distance for the three production blasts.

TABLE 2. - Analysis of variance--airblast data

Source	Sum of squares (SS)	Degrees of freedom (df)	Mean square (MS)	Computed F	Pass, $F_{0.05}(4,16)$
Combined.....	0.68471	4	0.17118	1.64	3.01
Error.....	1.88346	16	.10464	-	-
Total.....	2.56817	20	-	-	-

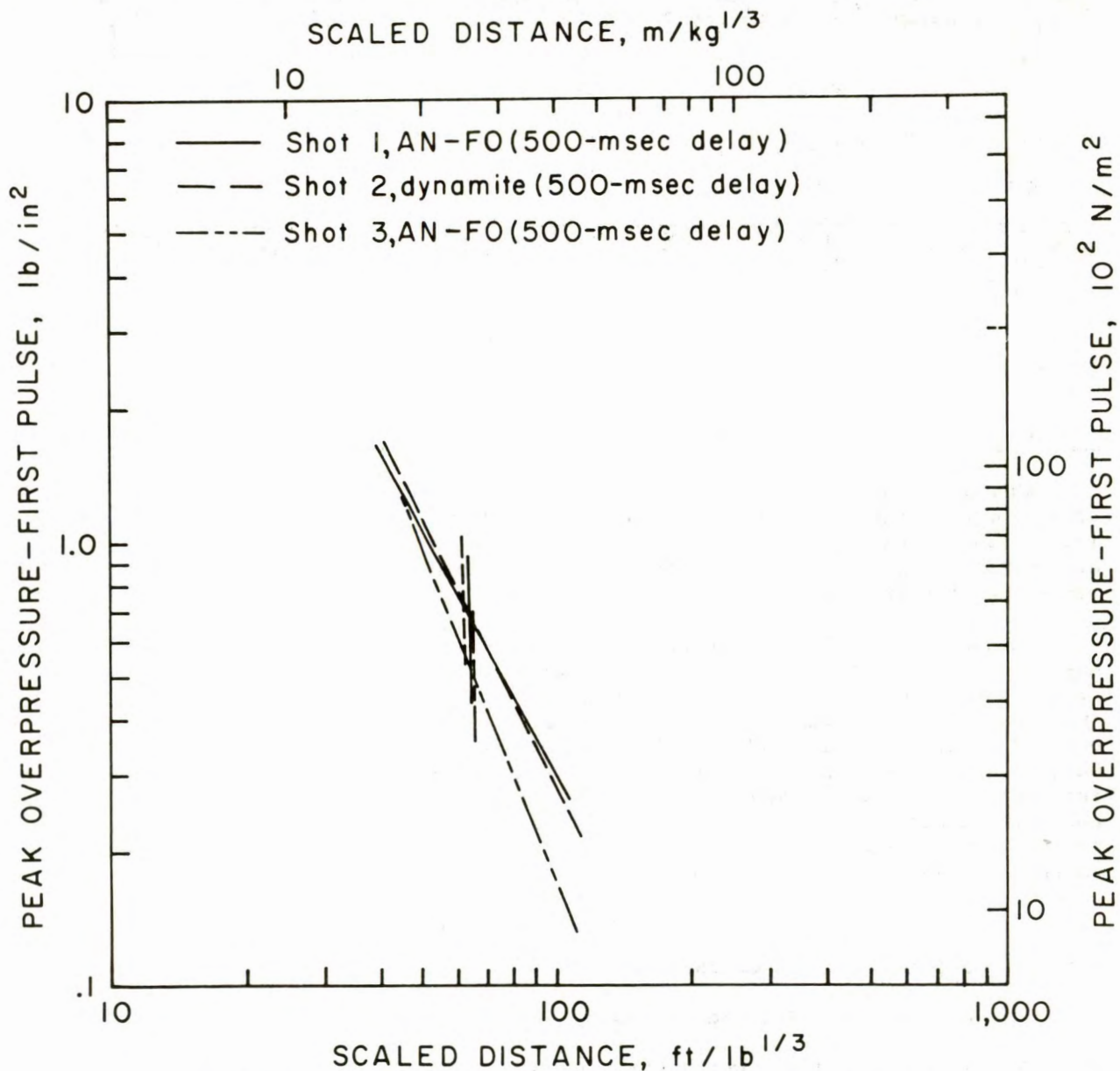


FIGURE 9. - Least-Squares Regression Lines for Shots Nos. 1-3.

Figure 10 shows the least-squares regression line through the combined overpressure data from the three blasts. The circles (open and solid) refer to the overpressures measured from the two AN-FO blasts, and the squares refer to the overpressures measured from the dynamite blast.

DISCUSSION

Comparison of Mine Blast Overpressures With Levels Produced by Surface Blasts

In underground mine production blasting, two important features influence the overpressure levels: the complex geometry surrounding the source and the confinement of the explosive charge.

The complex geometry tends to amplify the overpressure levels. The blast waves from an underground blast cannot spread out in a spherical or hemispherical pattern as on the surface. Underground blast waves are constrained by the excavated opening and forced to propagate, by reflection, down the mine drift. Because of the complex mine geometry, Hanna and Zabetakis (4) found that Sachs' cube-root scaling law tends to underestimate the overpressure levels produced by unconfined blasts in a large underground opening (40 ft (12 m) wide by 35-to-55 ft (10.7 to 16.8 m) high). Smaller room and pillar mine openings would probably amplify the overpressure levels even more.

Taylor (19) experimented with shock tubes having numerous geometrical configurations and found that focusing could produce extremely high (up to 10 times normal reflected amplitudes) short duration pulses. Focusing was most intense when the shock wave would approach the junction of two walls and a floor or a ceiling; a common geometry near underground mine ventilation barriers.

The confinement of the blast afforded by the rock to be blasted and any stemming in the shotholes tend to reduce the overpressure levels of underground production blasts. Ireland (6) conducted some simple experiments with small charges of dynamite (one stick) and found a sixfold reduction in pressure, at a given distance, between a charge buried about 1 ft (0.3 m) underground and the same charge detonated in the air. Ireland also observed that the wavefronts from the blasts detonated in air were much steeper than those from the confined blasts. The amount of overpressure reduction given by the confinement and stemming, however, has not been adequately determined for typical underground blasts.

The underground geometry and blast confinement at White Pine were fairly typical of those in an underground room and pillar mine. The mine geometry in the test area was relatively simple, comprising a long, almost straight haulageway intersected at right angles by several crosscuts. The excavated openings were approximately 28 ft (8-1/2 m) wide by 8 ft (2-1/2 m) high. Although no stemming agent was employed, the production blasts used in LH-1 were well confined by the "V" cut blast pattern and the bulk of the total charge was concentrated in the first delay.

The rapid falloff of first pulse overpressures with distance for the blasts seemed largely due to the levels measured at gage stations 6 through 8. These gages were located around a slight curve in the haulageway. The first arrival could not have been the direct wave but more likely was a reflection of the direct wave off the rib of LH-1. Waveforms from these gages were more complex than those recorded at the closer gage stations and often had secondary arrivals with slightly higher amplitudes than the initial pulses. Because the analysis was limited to only the first pulse amplitudes, the rate of attenuation for the overpressures was greater than might have been observed if the haulageway had been straight.

The highest overpressure levels from the 500-msec single-heading blasts were recorded at gage stations 1 through 5 along the straight portion of the haulageway, and ranged from about 0.7 lb/in^2 (approx. $48 \times 10^2 \text{ N/m}^2$) to about 1.75 lb/in^2 (approx. $120 \times 10^2 \text{ N/m}^2$). These measured levels, most of which were recorded at scaled distances less than $60 \text{ ft/lb}^{1/3}$ ($31 \text{ m/kg}^{1/3}$), can provide some idea of the damage potential of overpressures associated with routine production blasts in an underground mine such as White Pine.

Although underground mines have few, if any, structures with windows, a comparison with overpressures associated with window damage seems useful because windows are probably the first part of a structure damaged from airblast. The comparison could provide a convenient reference for discussing the damage potential of the blast.

In early experiments with surface blast waves, where the main airblast disturbance consisted of a positive pressure pulse lasting only a few milliseconds, Windes (21) found no damage to experimental window boxes when this overpressure was 0.7 lb/in^2 ($48 \times 10^2 \text{ N/m}^2$) or less. Further results of his study demonstrated that positive damage to the boxes occurred when the maximum pressure reached 1.5 lb/in^2 ($103 \times 10^2 \text{ N/m}^2$). Windes felt that a tentative index of window damage for blasts involving small (1 to 50 lb (approx. 0.454 to 22.7 kg)) quantities of dynamite was 1.0 lb/in^2 ($69 \times 10^2 \text{ N/m}^2$) maximum pressure.

In a later study, Windes (22) observed that window glass failure occurred before any other structural failure and could be regarded as the first threshold of damage from excessive overpressure. Windes' data also demonstrated that a pressure of 2 lb/in^2 ($138 \times 10^2 \text{ N/m}^2$) could be established as a definite point at which window failure could be expected.

Glass breakage, however, may be a function of factors other than overpressure levels such as condition of windows and duration of impulse. In a recent study, Reed and coworkers (16) analyzed the window pane damage to residences and factories in San Antonio resulting from the accidental detonation of 111,500 lb (approx. 50 520 kg) of chemical high explosives. Overpressures were calculated from the explosive yield and the atmospheric conditions at the time of detonation. Most of the observed glass damage occurred in areas having the rather low calculated incident blast overpressures of 0.028 to 0.069 lb/in^2 (approx. 190 to 480 N/m^2). Reed felt that some of this damage could be attributed to such factors as faulty window

maintenance in low-income housing areas. But assuming that the actual pressures were close to the calculated values, substantial evidence existed to indicate that rather low pressure levels apparently could have caused significant window damage.

As part of the Bureau's study of blasting vibrations and their effect on structures, Nicholls, Johnson, and Duvall (10) analyzed airblast data and damage reports from numerous sources. They concluded that glass damage was quite sensitive to window condition. Properly mounted panes failed at overpressures of 0.75 lb/in² (approx. 52×10^2 N/m²). Panes forced into frames and secured under constant strain were subject to cracking at overpressures of 0.1 lb/in² (approx. 690 N/m²). Airblast pressures of only 0.03 to 0.05 lb/in² (approx. 210 to 340 N/m²) were capable of vibrating a loose window sash. The Bureau concluded that for windows in reasonably good condition, some panes of glass would fail at 0.75 lb/in² (approx. 52×10^2 N/m²), and almost all panes would fail at 2.0 lb/in² (138×10^2 N/m²).

Based on this analysis of measured airblast overpressures, Nicholls, Johnson, and Duvall recommended an overpressure level of 0.5 lb/in² (approx. 34×10^2 N/m²) as a reasonably safe airblast pressure level for most quarry production blasting operations. The Bureau also concluded that airblast is not a significant factor in causing damage to residential structures for most routine, well confined quarry blasts.

Hirsch (5) reviewed numerous studies of airblast effects on the ear structures of animals and humans. He concluded that the threshold pressure for damage to human ear structures was about 5 lb/in² (approx. 340×10^2 N/m²). Some of the data, however, indicated that damage may often have occurred to the inner ear without demonstrable injury to the middle ear. Hirsch recommended that ear protection be used when gun crews are exposed to muzzle blast overpressures of 4 lb/in² (approx. 280×10^2 N/m²).

The waveforms recorded at White Pine were much more complex and were of longer duration than the shapes recorded in open air. The impulse, an important aspect of the damage-causing ability of the blast, may become the controlling factor under some conditions (7). Because the impulse per unit of projected area is the area under the pressure-time curve, the slow decay of the overpressures from the underground blasts means higher impulse values. As a result, the underground overpressure levels may have higher damage potentials than for similar maximum overpressure levels recorded from surface blasts. Using results of a study of blast effects on aircraft, Sewell and Kinney (18) concluded that the damage potential of an explosive blast for a specified target is not simply a function of peak overpressure, but is a combination of peak overpressure, the decay characteristics of the blast wave, and the dynamic response of the target structure.

The highest overpressure levels from the White Pine single-heading 500-msec blasts (0.7 to 1.75 lb/in² (approx. 48×10^2 to 120×10^2 N/m²)) roughly corresponded to the levels Windes associated with probable damage to experimental window blasts from small surface blasts. However, the levels were much greater than the calculated overpressures Reed and coworkers (16)

associated with residential and factory window damage from a large chemical explosion. The White Pine levels were also above the reasonably safe level of 0.5 lb/in^2 (approx. $34 \times 10^2 \text{ N/m}^2$) recommended by the Bureau to minimize window damage from quarry blasting.

The magnitude of the recorded overpressure levels and the importance of wave decay characteristics on damage potential indicate that the 500-msec single-heading blasts could be considered a potential or contributing damage factor for mine structures such as foam ventilation barriers. Because routine production blasting operations are usually conducted by firing multiple-heading, 25-msec blasts, the damage potential from routine operations would be higher than that associated with the single-heading test blasts fired in LH-1.

Although the highest overpressures from the White Pine blasts were lower than the 5 lb/in^2 (approx. $280 \times 10^2 \text{ N/m}^2$) level Hirsch associated with damage to the middle ear of humans, the levels were roughly the same order of magnitude. The airblast levels from the single-heading blasts indicate that if routine production blasting (that is, firing multiple headings) were to be conducted from close range, ear protection should be worn by mining personnel as a precautionary measure.

Possible Procedures To Reduce Airblast Damage to Underground Structures and Personnel

To design blastproof underground structures and to maintain a safe working environment for miners detonating blasts, some method of predicting overpressures and impulses associated with routine underground production blasting is needed. Because of frequent damage claims resulting from sonic booms and quarry blasting, many studies have been conducted on airblast waves (in free air) from confined and unconfined sources. The Bureau feels that additional research is needed to provide similar knowledge on airblast in underground mines.

Although underground mines normally have few production-line structures involved with mining the ore that would be susceptible to damage from airblast, many mines prefer to use ventilation barriers (foam-brattice stoppings), which seem to be affected by blasting (8). Most of the problems occur when the stoppings are positioned near new development areas where abnormally heavy blasting operations (often multiple headings) are conducted.

The brattice cloth on metal lath stopping, when coated with rigid foam, is as impervious as a concrete block stopping made with mortared joints and coated with gunite. The cost saving inherent in the foam stopping is due partly to the lower labor costs: A foam-brattice stopping of a 100-ft^2 (9.29-m^2) area can be constructed in 1 man-hour, whereas a block stopping (without mortared joints) with a coating of gunite requires 8 man-hours. The concrete block stopping, however, is more resistant to shock pressure from heavy blasting. Many of the stoppings at White Pine were made by bulldozing a pile of muck into the opening, and closing the top space with a foam-brattice stopping. Attempts to eliminate damage by techniques such as inclusion of barrels in the foam barrier proved unsuccessful.

Because of the lower cost and good ventilation effectiveness of the foam stoppings, mining companies should attempt to lower the overpressures caused by blasting when they cause damage to the form walls. Savings will be realized in decreased maintenance costs. Better ventilation will also be achieved throughout the mine if the stoppings are not damaged by the development blasting.

Mining companies troubled with damage to foam ventilation stoppings, or companies conducting blasting operations at close range to the shot locations should consider experimentally testing the effectiveness and practicality (for their particular operation) of the following procedures, which could reduce overpressure levels from blasting.

1. Use 500- rather than 25-msec delay caps to reduce the possibility of waveform reinforcement from subsequent delay periods.

2. Because the experiments at White Pine demonstrated that only the zero-delay charge weight of the 500-msec-delayed round produced high overpressure levels, blasts with smaller zero-delay charge weights could reduce the damage potential.

3. Avoid blasting several headings in the same immediate area simultaneously. In the normal production operation, single firing is hard to manage; however, if some automated firing method could be found to fire the headings in sequence, overpressures might be reduced.

4. Where feasible, stemming should be used in the shotholes (at least in the zero-delay holes) to further reduce the strength of the blast source.

SUMMARY

The recorded waveforms from the 500-msec production blasts demonstrated that only the charge detonated by the zero-delay caps produced high overpressures. Most gages recorded high amplitude signals for about 100 msec after the arrival of the first pulse. Because of the complex mine geometry, the waveforms were generally more complicated than the quasi-exponential pulse typical of blasts detonated in open air. The gages located in the straight portion of the haulageway recorded the simplest waveforms--the maximum amplitudes were almost always associated with the first (direct) pulse. The waveforms from the more distant gages contained numerous secondary arrivals, some of which were of greater amplitude than the first pulse.

The highest overpressure levels produced by the confined underground blasts (0.70 lb/in^2 (approx. $48 \times 10^2 \text{ N/m}^2$) to 1.75 lb/in^2 (approx. $120 \times 10^2 \text{ N/m}^2$)) were much greater than levels associated with damage to residential and factory windows from a large accidental surface blast. The levels were roughly comparable with those associated with damage to experimental window boxes in controlled tests. The levels from the White Pine blasts exceeded the 0.5 lb/in^2 (approx. $34 \times 10^2 \text{ N/m}^2$) overpressure level recommended by the Bureau to minimize window damage from routine quarry blasting.

The waveforms recorded at White Pine were more complex and were of longer duration than the shapes normally recorded in open air. Because the impulse (the area under the pressure-time curve) may become the controlling factor in the damage-causing ability of the blast, the slow decay of the overpressure waves from the underground blasts mean higher impulse values resulting in higher damage potentials than for similar maximum overpressure levels recorded from surface blasts. The overpressure levels of the single-heading blasts, the slow decay of the recorded waveforms, and the possible impulse focusing effects of the underground environment indicate that multiheading production blasts could constitute considerable damage potential to mine structures such as foam ventilation barriers.

Although the highest overpressures from the single-heading blasts were lower than the 5 lb/in² (approx. 280×10^2 N/m²) level associated with damage to the middle ear of humans, the levels were roughly the same order of magnitude. These levels indicate that if detonation of multiple heading production blasts were to be conducted from close range, ear protection should be worn, at least as a precautionary measure, by blasting personnel.

The mine geometry (a curvature in the haulageway) seemed to affect the peak overpressures for the more distant gages. The most representative levels existed in the straight portion of the haulageway where the first pulse amplitudes were due to waves that had traveled a more direct path from the blast to the gage.

An analysis of variance of the airblast overpressures from the three production blasts showed that no statistically significant difference existed between the levels from the dynamite and AN-FO blasts. A single equation,

$$P = 4.9 \times 10^3 (D/W^{1/3})^{-2.15}, \quad (2)$$

where P = overpressure in pounds/inch²,

D = distance in feet,

and W = zero-delay charge weight in pounds,

could be used to describe the falloff of overpressure with distance for the three White Pine blasts. In SI units, the prediction equation for overpressures from the three White Pine blasts becomes,

$$P = 2.6 \times 10^6 (D/W^{1/3})^{-2.15}, \quad (3)$$

where P = overpressure in newtons/meter²,

D = distance from the blast in meters,

and W = zero-delay charge weight in kilograms.

Because of the small sample size (only 3 shots) the statistical conclusions of this report should not be regarded as proof that the overpressure levels for AN-FO and dynamite blasts would always be this closely comparable.

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