

REPORT DOCUMENTATION PAGE		1. REPORT NO. BuMines OFR 103(4)-79	2.	PB299890 	
4. Title and Subtitle Control of Vibration and Blast Noise From Surface Coal Mining Executive Report			December 1978		
7. Author(s) John F. Wiss and Patrick Linehan			6.		
9. Performing Organization Name and Address Wiss, Janney, Elstner and Associates, Inc. 330 Pflingsten Road Northbrook, IL 60062			5. Performing Organization Rept. No.		
12. Sponsoring Organization Name and Address Office of the Assistant Director--Mining Bureau of Mines U.S. Department of the Interior Washington, D.C. 20241			10. Project/Task/Work Unit No.		
			11. Contract(C) or Grant(G) No. (C) J0255022 (G)		
15. Supplementary Notes Approved by the Director of the Bureau of Mines for placement on open file August 9, 1979.			13. Type of Report & Period Covered Contract research 7/1/75 - 2/28/78		
			14.		
16. Abstract (Limit: 200 words) A series of controlled experiments was conducted at four surface coal mines to study the effects of certain blast parameters upon the ground and air vibration. Preliminary scale-model blasts were conducted at a quarry to provide basic data. This report presents an analysis of the data obtained from the field tests. Where possible, expressions have been developed that will be helpful in establishing guidelines for the design of blasting to minimize adverse results with respect to noise and ground vibration.					
17. Document Analysis a. Descriptors Blasting vibrations Blast noise Surface coal mines b. Identifiers/Open-Ended Terms c. COSATI Field/Group 08I -/					
18. Availability Statement Release unlimited by NTIS.			19. Security Class (This Report) Unclassified		22. Price A03-A01
			20. Security Class (This Page) Unclassified		

CONTROL OF VIBRATION AND BLAST NOISE

FROM SURFACE COAL MINING

Executive Report

Prepared for:

United States Department of the Interior
Bureau of Mines

by

Wiss, Janney, Elstner and Associates, Inc.
330 Pfingsten Road
Northbrook, Illinois 60062

Final Report

Contract No. JO255022

December 1978

Bureau of Mines Open File Report 103(4)-79

"The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Interior Department's Bureau of Mines or of the U.S. Government."

FOREWORD

This report was prepared by Wiss, Janney, Elstner and Associates, Inc., Northbrook, Illinois 60062, under USBM Contract No. J0255022. The contract was initiated under the Environmental Research - Mining Environmental Control Technology Program. It was administered under the technical direction of the Twin City Mining Research Center, with Mr. David E. Siskind (who succeeded Mr. Joseph L. Condon) acting as the Technical Project Officer. Mr. William P. Battle was the Contract Administrator for the Bureau of Mines.

This report, which is identified as the "Executive Report", summarizes the findings of this research program. The "Technical Report" gives the field experimental procedures, the test data, and the detailed analyses developed as a result of each investigation. Chapters of the Technical Report are referenced in this report during the discussions of specific blast variables.

This report is a summary of the work recently completed as part of this contract during the period July 1, 1975 to February 28, 1978. The Technical Report was submitted by the authors in December, 1978.

The authors wish to express their appreciation to the management and personnel of the Lehigh Stone Operations operated by the Western Material Company, the Sahara Mine No. 6 operated by the Sahara Coal Company, Inc., the Burning Star No. 4 Mine operated by the Consolidation Coal Company, the Tebo Mine operated by the Peabody Coal Company, and the Fabius Mine operated by Robertson and Associates, Inc. This project could not have been conducted without their cooperation and assistance. The staff of WJE who were actively engaged in this program are also commended for their contributions to the project. Particular acknowledgement is made of the invaluable guidance and assistance of Mr. Wilbur I. Duvall, who was Consultant on this project.

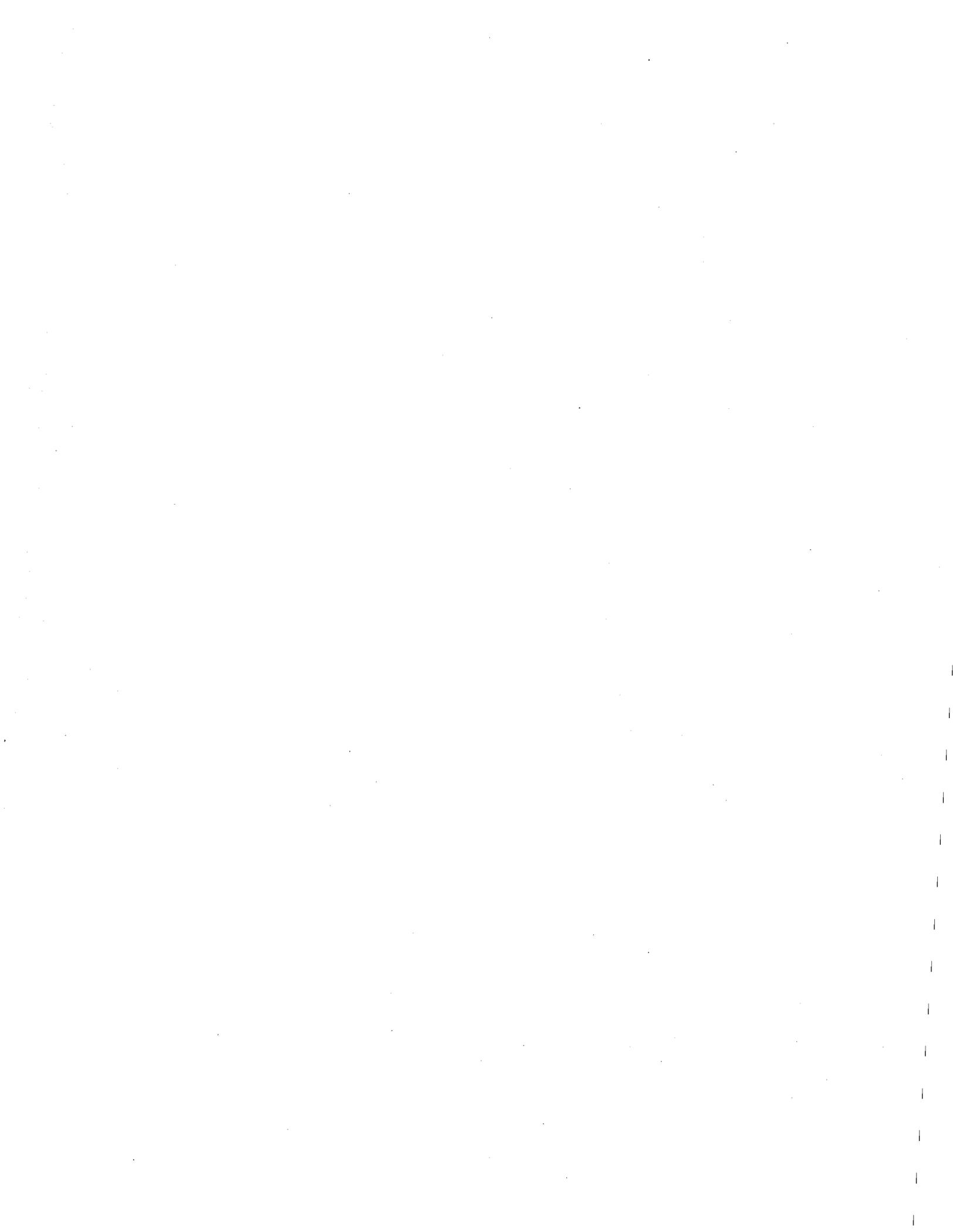


TABLE OF CONTENTS

<u>Chapter</u>	<u>Page</u>
1 - Synopsis	5
2 - Background	5
3 - Objectives	8
4 - Scope	8
A. Phase I - Literature Research	10
B. Phase I - Test Plan	10
C. Phase II - Field Tests	11
5 - Instrumentation	12
6 - General Statistical Procedures	13
7 - Generation and Propagation of Ground and Air Vibration	13
8 - Charge Weight Per Delay	16
9 - Total Charge Weight Per Blast	22
10 - Charge Depth	22
11 - Charge Length and Diameter	28
12 - Length of Delay	28
13 - Effect of Resonance with Delay Interval	32
14 - Burden and Spacing	32
15 - Attitude (Angle of Borehole)	35
16 - Directional Effects	36
17 - Stemming	37
18 - Bare vs Covered Detonating Cord	38
19 - Surface Winds	40
20 - Surface Terrain	41
21 - Type of Overburden	43
22 - Reinforcing of Overpressures from Millisecond Delay Blasts	43
23 - Frequency Composition of Ground and Air Vibration	46
24 - Recommendations	47

ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
8-1 - Peak Particle Velocity vs. Scaled Distance, Vertical Component, Consol, Fabius, Sahara and Tebo Mines	18
8-2 - Peak Particle Velocity vs. Scaled Distance, Vertical Component, Consol, Fabius, Sahara and Tebo Mines	18
8-3 - Positive Overpressure Uncorrected for Scaled Depth of Burial vs. Scaled Distance, Consol, Fabius and Tebo Mines	19
8-4 - Negative Overpressure Uncorrected for Scaled Depth of Burial vs. Scaled Distance, Consol, Fabius and Tebo Mines	19
10-1 - Positive Overpressure Uncorrected for Scaled Depth of Burial vs. Scaled Distance, Consol, Fabius and Tebo Mines	25
10-2 - Positive Overpressure, Corrected for Scaled Depth of Burial, vs. Scaled Distance, Consol, Fabius and Tebo Mines	25
10-3 - Overpressure Ratio vs. Scaled Depth of Burial	26
12-1 - Typical Instrument Positions and Firing Angles for a 3-hole Blast, with a Firing Sequence of 1-2-3 from Left to Right	30
14-1 - Blast Pattern Geometry and Critical Angles for Example Problems (Overpressure)	34
20-1 - Surface Terrain Profiles Along Instrument Array	42
22-1 - Comparison of Recorded Overpressure Time History with Simulation, Blast F5L	45

CHAPTER 1 - SYNOPSIS

The research program reported herein consisted of four elements of study. The first was a literature review, the second was a series of tests during which air overpressure and ground vibration resulting from specially designed controlled blasts detonated in a stone quarry were measured. The third consisted of overpressure and ground vibration measurements made in four operating surface coal mines during the course of normal production blasting operations. The fourth element was the analysis of the data obtained from the field tests. The analysis was directed toward the development of relationships between air and ground vibration and a number of variables, which were known or suspected to influence these vibrations from blasting at the mines. Where possible, expressions have been developed which will be helpful in establishing guidelines for the design of blasting to minimize adverse results with respect to noise and ground vibration.

The significance of each of the many variables considered in this research program to the development of noise and ground vibration in broad general terms was found to be as shown in the following tabulations.

CHAPTER 2 - BACKGROUND

The projected need for coal as a stable domestic source of energy anticipates increased production at existing surface mines and the opening of new large-scale surface coal mines. As a result of the expansion of these operations, it is also anticipated that the blasts required to break the overburden will be more frequent and possibly larger.

Ground vibration and blast noise are produced by such blasting operations. These phenomena, when felt or heard, may be considered as having an adverse effect on the environment in certain instances.

Limited information on the methods of reducing air blast and ground vibration has been available to the mine operators. The most recent information was published by the U. S. Bureau of Mines in 1971⁽¹⁾. Their investigation was primarily concerned with ground vibration, but some effort was devoted to air vibration (blast noise).

(1) Nicholls, H. R., Johnson, C. G., Duvall, W. I., "Blasting Vibrations and Their Effects on Structures", Bulletin 656, U. S. Department of the Interior, Bureau of Mines, 1971.

Variables within the control of mine operators	Influence on ground motion		
	Signif.	Moderately signif.	Insignif.
1. Charge weight per delay	X		
2. Length of delay	X		
3. Burden and spacing		X	
4. Stemming (amount)			X
5. Stemming (type)			X
6. Charge length and diameter			X
7. Angle of borehole			X
8. Direction of initiation		X	
9. Charge weight per blast			X
10. Charge depth			X
11. Bare vs. covered detonating cord			X
<hr/>			
Variables not in control of mine operators			
1. General surface terrain			X
2. Type and depth of overburden		X	
3. Wind			X

Variables within the control of mine operators	Influence on overpressure		
	Signif.	Moderately signif.	Insignif.
1. Charge weight per delay	X		
2. Length of delay	X		
3. Burden and spacing	X		
4. Stemming (amount)	X		
5. Stemming (type)		X	
6. Charge length and diameter			X
7. Angle of borehole			X
8. Direction of initiation	X		
9. Charge weight per blast			X
10. Charge depth	X		
11. Bare vs. covered detonating cord	X		
<hr/>			
Variables not in control of mine operators			
<hr/>			
1. General surface terrain		X	
2. Type and depth of overburden	X		
3. Wind	X		

CHAPTER 3 - OBJECTIVES

This research program was initiated to determine principally by experiment those factors which significantly affect the generation of air blast and ground vibration and the interaction between them. Further experimentation was directed toward evaluating parameters which can be varied in developing blasting techniques to minimize the magnitude of vibration and blast noise without preventing suitable breakage to permit the rapid handling of overburden and coal by conventional surface mining equipment.

The test sites were geographically located to represent current surface coal mine blasting practices in the Interior Coal Province. This qualification was specified because of the proximity of the mining in this area of the Nation to populated areas where the adverse environmental effects may attract the most attention.

The purpose of this study is to assess the many variables which can influence noise and ground motion levels with the view that such evaluation will assist mine operators in designing necessary blasting procedures to mitigate the consequential effects to the maximum extent.

CHAPTER 4 - SCOPE

The material prepared by the Bureau of Mines in preparation for this study included a number of variables recognized as possibly being factors which would influence the noise and ground motion levels resulting from blasting associated with surface coal mining. In the process of developing the preliminary test plan (Phase I of this program), several other variables were added by the contractor. Furthermore, as is the case with all research projects, developments during the progress of the work revealed that other variables should be evaluated and that some originally considered could not or need not be included.

The following variables were included in the analysis of the data obtained from the tests conducted throughout the progress of the program reported herein:

Variables Under the Control of Mine Operators

1. Charge weight per delay*
2. Length of delay*
3. Stemming*
4. Charge weight per blast
5. Directional effects
6. Burden and spacing*
7. Charge depth*
8. Attitude (angle) of borehole*
9. Bare vs. covered detonating cord
10. Charge length and diameter

Variables Not Under Control of Mine Operators

1. Surface terrain
2. Surface winds
3. Type of overburden*

Each of the above variables was given consideration in evaluating the data obtained from the many field tests conducted during the period of this research program. In addition, assessment of the levels of measured noise and ground motion included analysis of:

1. Interaction between air and ground vibration
2. Surface particle velocity at source
3. Reinforcing of air blast overpressures

* Suggested by the U. S. Bureau of Mines

The scope of the work was divided into two phases. Phase I was the plan development; Phase II was the experimental testing in the field. It was required that Phase I be completed, reported, and approved before Phase II was started. However, in common with all research, the test plan was modified somewhat during the course of the study as analysis of data or field conditions beyond the control of the researchers dictated.

A. Phase I - Literature Research

A literature review of references pertinent to the program was made at the outset of this study to provide information on data reported by others. These data were considered in the analysis of the data obtained during the course of the work accomplished for this program.

The literature review and bibliography resulting from the literature search is presented in Appendix G of the Technical Report.

B. Phase I - Test Plan

The technical proposal suggested that some of the parameters to be evaluated could best be investigated by scale-model experiments conducted at a quarry where maximum control could be maintained, while others could only be evaluated from data obtained during blasting done at operating surface coal mines. A preliminary Data Plan of these controlled scale-model experiments was prepared as part of Phase I.

Since specific mines had not been selected for the full-scale experiments at the time the preliminary Test Plan was developed, this plan could only generally describe the nature of the contemplated experiments.

Not more than four surface mines were to be selected for the experimental field testing. The techniques used to select the mines were as follows. A letter, generally describing the project and its goals, was sent to a number of the large coal companies in the Interior Coal Province. Forms requesting information on the geology, blasting operations, and the attitude of the mine regarding the program were enclosed with the letter. Twelve mine operators, who responded and indicated willingness to cooperate, were visited to obtain additional information and to evaluate the specific sites as to their suitability for the studies, and to further pursue the willingness of the mine officials to cooperate with the research program. Of the twelve mines visited, only six were found to be suitable for the experiments planned for this project.

Four of the six mines were selected and recommended to the Bureau, and cooperative agreements were reached with the mining companies. These mines were Tebo, Sahara, Consol (Burning Star No. 4),

and Fabius. The mines were operated by Peabody Coal Company, Sahara Coal Company, Consolidation Coal Company, and Robertson and Associates, respectively.

The Phase I Test Plan report related: (a) detailed information on the mines investigated and recommended, (b) descriptions of instrumentation and data processing techniques, (c) a revised Data Plan for the scale-model tests, and (d) a Data Plan for the full-scale tests. The Phase I report was approved by the Contracting Officer on December 10, 1975, and Phase II was begun.

C. Phase II - Field Tests

The scale-model tests were started in December, 1975 at the Lehigh Stone Operations of Western Materials Company. Some full-scale experiments at the mines were conducted between scale-model tests. Due to problems at the mines associated with production scheduling and weather, this practice was deemed appropriate. After completion of the scale-model tests, the experiments were conducted at the mines as scheduling and opportunities to conduct specific experiments permitted.

A total of 155 blasts were detonated for the scale-model tests. The hole diameters, hole depths, and spacing were such that the scale factor may be assumed to be in the 1/4 to 1/5 range when compared with the range of these dimensions normally encountered at surface coal mines.

The following controllable variables were included in the design of these tests:

1. Depth of charge
2. Covered vs. exposed detonating cord
3. Angle of borehole
4. Charge length
5. Charge diameter
6. Amount of stemming
7. Type of stemming

Some of these same variables were evaluated to the extent possible from data obtained during the full-scale tests in operating mines.

A total of 111 blasts were monitored during normal operations in the four surface mines selected for these tests. The following variables were evaluated from the data obtained from these blasts.

1. Charge weight per delay
2. Length of delay
3. Charge weight per blast
4. Directional effects
5. Burden and spacing
6. Charge depth
7. Angle of borehole
8. General shot layout
9. Surface terrain
10. Surface winds
11. Type of overburden

CHAPTER 5 - INSTRUMENTATION

This chapter describes the instrumentation used for the field acquisition of data and the laboratory data reduction. The field data acquisition systems primarily consisted of recording the ground vibration and overpressure and blast noises at five positions simultaneously. At all positions, the data was recorded on 4-channel seismographs. At two of the positions, the data was also recorded on magnetic tape. Supplementary data recorded included surface weather data, high-speed movies, detonation (zero) time, ground surface acceleration, and synchronous times at the recording positions. The details and specifications of the recording instrumentation and supplementary test equipment are given in Chapter 2 of the Technical Report.

Data was processed in the laboratory by two methods. The amplitudes of ground vibration and overpressure were manually reduced from the analog recordings. A frequency spectrum analyzer was used to identify the frequency composition of the seismic and overpressure data from the magnetic tape recordings.

CHAPTER 6 - GENERAL STATISTICAL PROCEDURES

The test data which were obtained at the scale-model test site and at the surface coal mine sites to meet specific experiment objectives were evaluated using statistical techniques. These evaluations generally include regression and variance analyses, as well as other specific techniques considered most appropriate for the particular set of data. The procedures used to evaluate the data were similar, and many of the techniques were identical for the analysis of each experiment objective. Chapter 3 of the Technical Report discusses the general sequence of the analyses and the specific statistical tests and resulting inferences.

CHAPTER 7 - GENERATION AND PROPAGATION OF GROUND AND AIR VIBRATION

The scale-model tests which utilized single-hole blasts provided the opportunity to study the mechanics of the generation and propagation of the ground and air vibration. When a buried explosive is detonated in a cavity in earth materials, the resulting high pressure and temperature explosion gases produces crushing and fracturing of the earth materials, generating a seismic pulse which travels outward in all directions. This seismic pulse is composed of both a longitudinal and a shear wave, and these waves are reflected from the free surface of the earth. Depending upon the depth of burial of the explosive, a crater may be produced at the surface above the blast. The seismic pulse decreases in amplitude with increasing distance from the blast. The rate of decrease of the amplitude with the distance is called the distance propagation equation, and is a power equation of the form:

$$A_v = K_v D^{-n_v} \quad (7-1)$$

where A_v = Maximum amplitude of a given component of ground vibration
 D = Travel distance
 K_v = Intercept
 n_v = Exponent of D

The intercept (K_v) is the value of the amplitude at a distance (D) of unity, and is a function of the charge weight, charge depth, and the characteristics of the earth material containing the charge. The exponent (n_v) is a function of the characteristics of the transmitting medium.

Air vibrations resulting from buried explosives are generated by several mechanisms. One is the vertical vibration of the free surface of the earth. The air vibration generated by the vertical component of the seismic wave at a gage position is identified as the Rock Pressure Pulse, or RPP. As a result of the vertical movement of the earth surface near the blast hole, an air vibration is generated which is identified as the Air Pressure Pulse, or APP, and is transmitted in all directions through the air. The escape of explosion gases through the borehole generates air vibration which is identified as the Stemming Release Pulse, or SRP. The escape of explosive gases through the fractured material in the crater zone also produces an air vibration which is identified as the Gas Venting Pulse, or GVP; this pulse is generally of a small amplitude and frequently is not discernable on the overpressure recording. When detonating cord is used on the surface of the earth, an air vibration is generated which is identified as the Detonating cord Pressure Pulse, or DPP.

The propagation equation for the air vibration is of the form:

$$A_p = K_p D_p^{-n_p} \quad (7-2)$$

where A_p = Maximum amplitude of a given polarity (positive or negative) of air vibration (overpressure)

D = Travel distance

K_p = Intercept

n_p = Exponent of D

The intercept (K_p) is the value of the amplitude of the overpressure at a distance (D) of unity, and is a function of the charge weight, charge depth, and the characteristics of the earth material containing the charge. The exponent (n_p) is a function of the characteristics of the transmitting medium. For the APP, SRP, GVP,

and DPP, the transmitting medium is air, and n is approximately equal to 1.0. The earth material is the transmitting medium of the seismic pulse which generates the RPP, and n_p is the same as for the vertical component of the ground vibration; for the scale-model tests conducted during this investigation, the values of both n_v and n_p are approximately 2.0.

The overpressure (RPP) generated by the vertical particle velocity of the earth surface for nominal temperature and atmospheric conditions is approximately equal to 0.0015 psi/in/sec of vertical ground motion. (See Appendix D-1 of Technical Report). Since the propagation velocity (speed) of the seismic pulse is greater than the speed of sound in air, the RPP is the first overpressure pulse to arrive at the gage position, and has the same frequency as the seismic wave. At close-in positions, it may also be the highest overpressure resulting from the blast.

The point of origin of the APP is at a horizontal distance from the blast hole, approximately equal to the depth of burial of the center of gravity of the charge rather than directly above the blast hole. Since the APP is air transmitted, and the propagation velocity in air is less than that through the earth materials, the APP arrives later than the RPP, and generally is of a lower frequency than the RPP.

The release of gas through the borehole produces the SRP and lags the APP by a time interval required for the top of the stemming to start to move. When the SRP occurs, it is a spike superimposed upon the APP. The GVP, which is the result of explosive gases escaping through the fractured material, also lags the APP by a time interval required for crevices to form in the fractured material through which the gases escape. If the explosives are buried relatively deep, resulting in minor mounding, the expanding gases will be at or near ambient atmospheric pressure by the time they vent, resulting in a small contribution to the overpressure.

Chapters 4-C and 4-D of the Technical Report give the field experimental procedures, test data, and the detailed analysis of the scale-model tests during which these phenomena were investigated.

The conclusions derived from this investigation regarding the generation and propagation of the ground and air vibration resulting from a blast can be summarized as follows:

1. Seismic and air pulses are developed which decrease in amplitude with increasing distance. A power equation form can be used to quantify the decay rate, which is a function of the characteristics of the earth material, for the ground vibrations and the RPP. The decay rate for the air pulses which are transmitted through the air from the source is less than for the seismic pulses.
2. The first pressure pulse to arrive at a gage position is ground-transmitted and is identified as the Rock Pressure Pulse (RPP). The RPP is generated by the vertical seismic vibration component at the gage position.
3. An air pressure pulse, defined as the APP, arrives at the gage position after the RPP pulse. The APP pulse is generated by the vertical ground movement in the vicinity of the blast hole and is air-transmitted to the gage position. Thus, a later arrival occurs because of the lower medium propagation velocity.
4. A stemming release pulse, SRP, which is caused by the release of the gas through the borehole, can occur with inadequate stemming. When the SRP occurs, it is a short duration pulse superimposed on the APP.
5. A gas venting pulse, GVP, is generated as a result of explosive gases escaping through the fractured material; it also lags the APP. The GVP is small, providing the charge is buried relatively deep.
6. When detonating cord is used in the blast, an air pressure pulse is generated which is identified as the DPP. For short lengths of detonating cord at the collar of the hole the DPP also lags the APP.

CHAPTER 8 - CHARGE WEIGHT PER DELAY

This chapter discusses the scaling laws applicable to the amplitudes of the ground and air vibration. The peak amplitudes of both ground and air vibration are determined primarily by the explosive weight per delay. Analyses were made for both average and maximum explosive weight per delay in a blast. For the blasts used in the analysis, the average explosive weight per delay gave slightly better

correlation with the amplitudes of ground and air vibration. In view of the minor improvement in correlation by using average explosive weights per delay, it was considered prudent to use the maximum explosive weight per delay for establishing propagation equations and predicting seismic and overpressure amplitudes from these propagation equations.

The experiment conducted to study the scaling factor consisted of using charge weights per delay in the ratios of 1, 2, and 4. Each series of tests was repeated using 17 ms, 33 ms, and 58 ms delay intervals. It was found from this experiment that cube root scaling was best for the seismic and overpressure data. An analysis of the seismic data was also made using the available data from all four mines. Figs. 8-1 and 8-2 show the vertical peak particle velocity vs. the scaled distance using cube root and square root scaling, respectively, for the different sites and instrument arrays at the four experimental mines. A group-by-group comparison of the correlation coefficients, using each scaling factor shows no appreciable differences. However, there was less total scatter in the seismic data from the different groups with square root scaling than with cube root scaling. This characteristic is illustrated in Figs. 8-1 and 8-2 by comparing the total amplitude spread near the center of the data.

The overpressure data from all the mines did not receive further analysis regarding a scaling relationship. However, the propagation laws were examined for the effects of the scaled depth of burial, which is discussed in Chapter 10 of this report. Figs. 8-3 and 8-4 show the positive and negative overpressure, respectively, vs. the scaled distance using cube root scaling from three of the four mines which used solid columns of explosives.

On the basis of these evaluations, it is recommended that square root scaling be used for the seismic propagation law and cube root scaling be used for the overpressure propagation law. However, as a matter of practicality, the use of cube root scaling is permissible for both the seismic and air vibrations within the range of the experimental data, which was approximately 200 to 1800 lbs per delay.

The scaled distance propagation equations for both seismic and air vibration are of the form:

$$y_i = I_i \left(D/W_d^\alpha \right)^{-n_i} \quad (8-1)$$

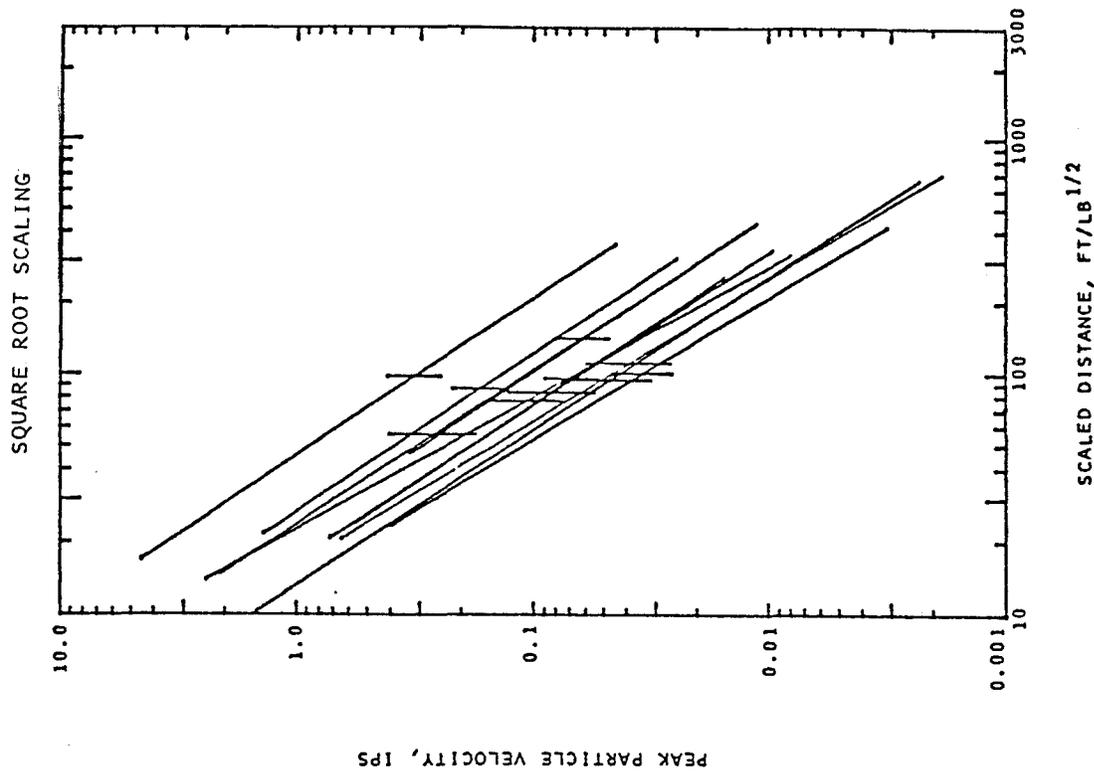


FIG. 8-2 - PEAK PARTICLE VELOCITY VS. SCALED DISTANCE, VERTICAL COMPONENT, CONSOL, FABIUS, SAHARA AND TEBO MINES

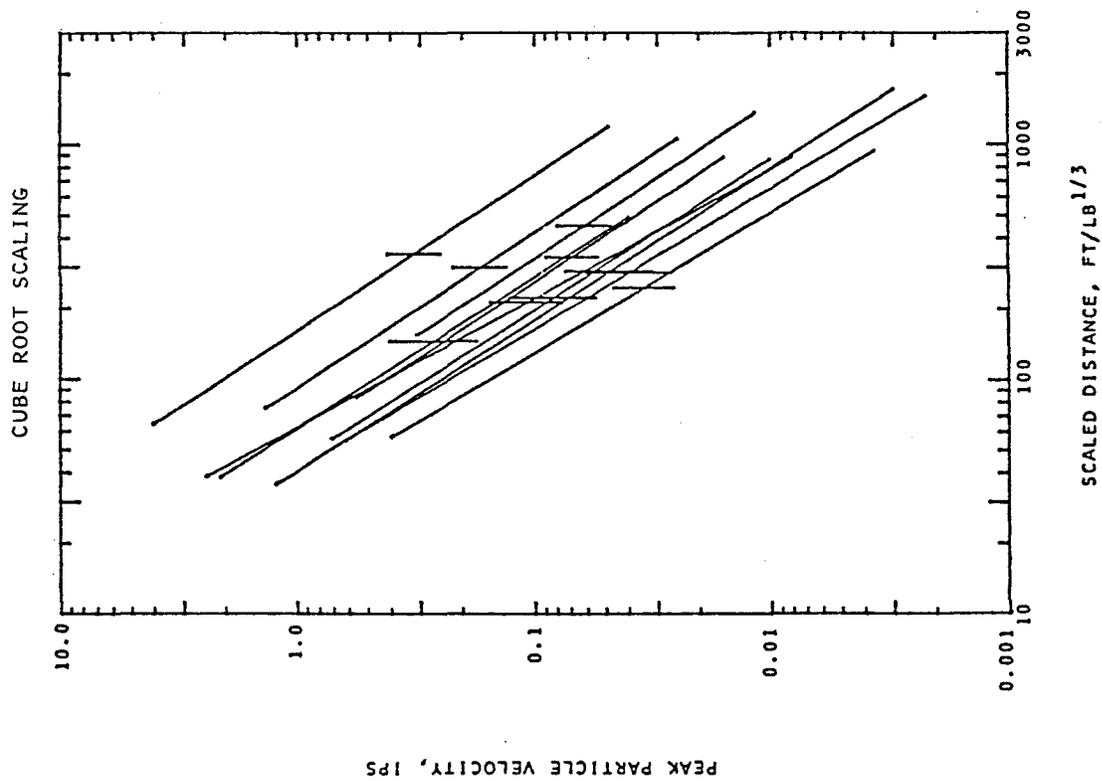


FIG. 8-1 - PEAK PARTICLE VELOCITY VS. SCALED DISTANCE, VERTICAL COMPONENT, CONSOL, FABIUS, SAHARA AND TEBO MINES

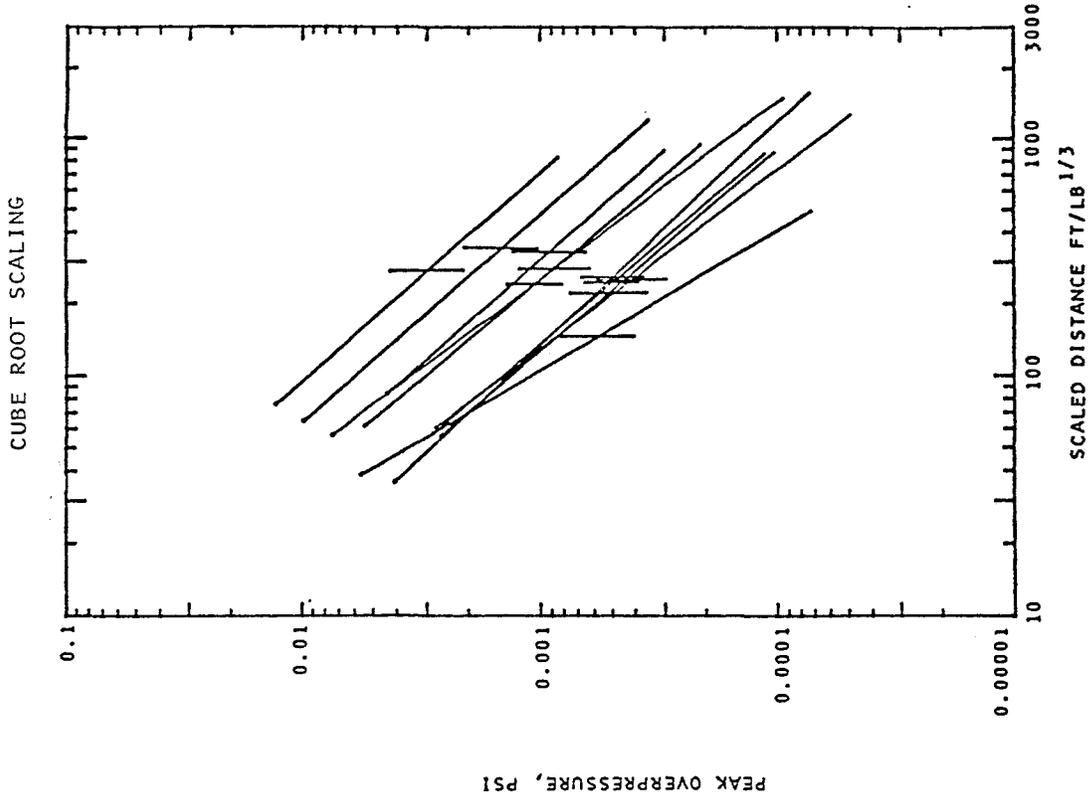


FIG. 8-4 - NEGATIVE OVERPRESSURE UNCORRECTED FOR SCALED DEPTH OF BURIAL VS. SCALED DISTANCE, CONSOL, FABIUS AND TEBO MINES

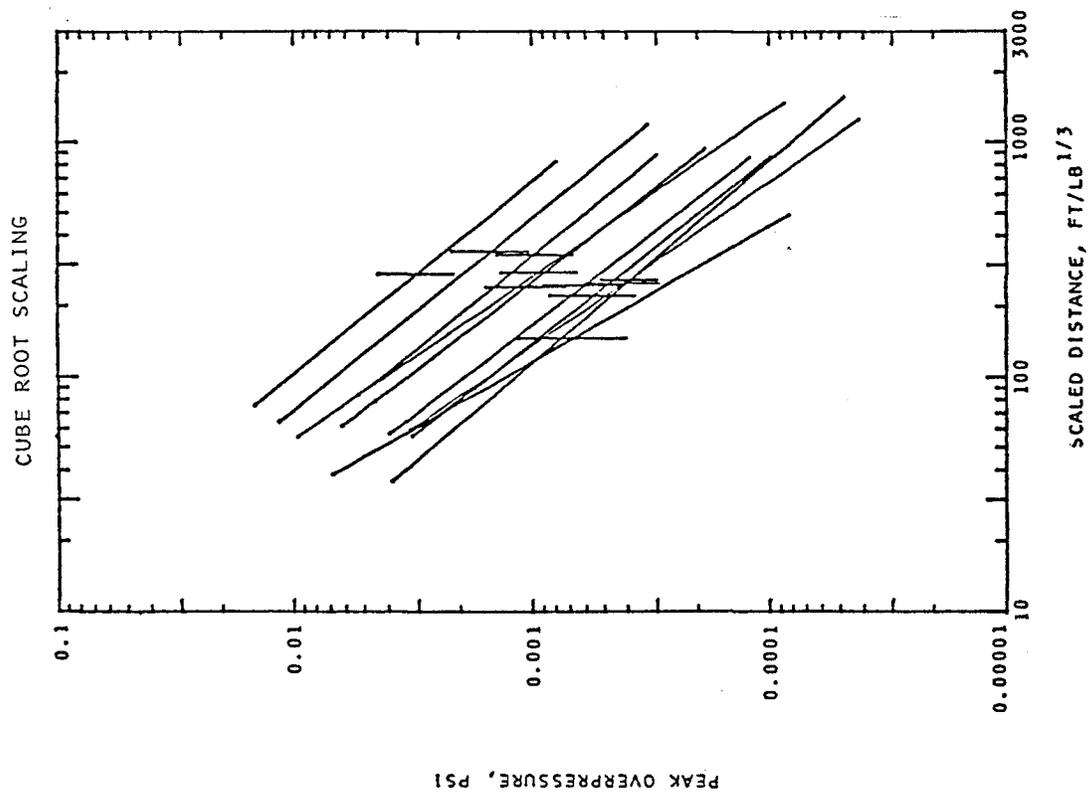


FIG. 8-3 - POSITIVE OVERPRESSURE UNCORRECTED FOR SCALED DEPTH OF BURIAL VS. SCALED DISTANCE, CONSOL, FABIUS AND TEBO MINES

where y = Peak particle velocity of ground vibration, in/sec, or peak overpressure, psi
 I = Intercept at $D/W_d^\alpha = 1$
 D = Travel distance from blast, ft
 W_d = Maximum charge weight per delay, lbs
 n = Exponent
 i = A particular component of ground vibration or overpressure
 α = Scaling factor, 1/3 for cube root scaling, 1/2 for square root scaling

The range of intercepts and slopes found during the tests at the different sites of the surface coal mines are:

CUBE ROOT SCALING

<u>Component</u>	<u>Intercept</u> <u>in/sec</u>	<u>Slope</u>
Radial	160 - 1656	1.324 - 1.729
Vertical	318 - 2176	1.512 - 1.823
Transverse	90 - 477	1.234 - 1.562
	<u>psi</u>	
+ Pressure	0.25 - 3.72	1.162 - 1.726
- Pressure	0.18 - 2.87	1.064 - 1.708

The range of the intercepts and slopes for the seismic data based on square root scaling are presented below:

SQUARE ROOT SCALING

<u>Component</u>	<u>Intercept</u> <u>in/sec</u>	<u>Slope</u>
Radial	44 - 281	1.324 - 1.729
Vertical	56 - 325	1.512 - 1.823
Transverse	19 - 106	1.234 - 1.562

The surface Mining Reclamation and Enforcement Provisions of the Department of the Interior, as published in the Federal Register dated December 13, 1977 (Part II), limits the maximum peak particle velocity of the ground motion in any direction to 1 ips in the immediate location of any dwelling, public building, school, church, or commercial or institutional building. It also limits air blast to 128 decibel (dB) linear-peak at any man-made dwelling or structure. Based on the results of this investigation, the limiting scaled distances to conservatively estimate a peak particle velocity of 1 ips and an air blast of 128 dB (0.007 psi) are reported below. The scaled distance values were established on the basis of two standard deviations above the mean line for the highest propagation equation for any of the mines.

<u>Scaling Factor</u>	<u>Scaled Distance</u>
<u>Seismic</u>	
Cube root	300 ft/lb ^{1/3}
Square root	75 ft/lb ^{1/2}
<u>Air blast</u>	
Cube root	300 ft/lb ^{1/3}

It is apparent that the scaled distance for both seismic and air blast is the same when cube root scaling is used.

The limiting scaled distances reported above were controlled by blasts using 9 ms delay intervals. The use of longer delay periods would result in smaller limiting scaled distances.

Chapter 5-E of the Technical Report gives the field experimental procedure, test data, and the detailed analysis developed during this investigation.

The conclusions developed from this investigation can be summarized as follows:

1. It is recommended that square root scaling be used for the seismic propagation law and cube root scaling be used for the overpressure propagation law. However, as a matter of practicality, the use of cube root scaling is permissible for both the seismic and air vibrations within the range of the experimental data, which was approximately 200 to 1800 lbs per delay.

2. The limiting scaled distance to conservatively estimate the ground vibration and airblast meeting the requirements of the Surface Mining Reclamation and Enforcement Provisions (1977) is $300 \text{ ft/lb}^{1/3}$ based on cube root scaling for both the ground and air vibration, or $75 \text{ ft/lb}^{1/2}$ based on square root scaling for the seismic vibration.

CHAPTER 9 - TOTAL CHARGE WEIGHT PER BLAST

Experiments were conducted in the surface mines in which the explosive weights per delay were held constant while the total weight in the blast was increased in the ratios of 1, 2 and 4. At one mine, the delay intervals were held constant at 17 ms and 58 ms. At the other mine, electric blasting caps were used which utilized delay intervals that ranged from 13 ms to 40 ms between charges in the same blasts.

Chapter 5-F of the Technical Report gives the field experimental procedures, the test data, and the detailed analyses for this investigation.

As a result of these experiments, it was found that the amplitude of the ground and air vibration was not significantly affected by total charge weight per blast, nor by the delay intervals investigated. Thus, the maximum charge weight per delay and not the total charge weight per blast controls the amplitudes of the ground vibrations and the overpressures.

CHAPTER 10 - CHARGE DEPTH

The effect of charge depth on seismic and air vibrations was analyzed. It was found that unless the depth of charge was well within the cratering zone, the ground vibrations were not significantly affected by the scaled depth of burial (B_s). The scaled depth of burial is defined as follows:

$$B_s = \frac{D}{W_h^{1/3}} \quad (10-1)$$

where D_{cg} = Depth to the center of gravity
of the charge

W_h = Weight of explosive in the
blast hole

Normally, for vertical holes, the depth to the center of gravity of the charge is equal to the length of the stemming (S), plus 1/2 the length of the charge (L_c). Thus, the equation used to compute the depth of burial for these charges is:

$$B_s = \frac{S + L_c/2}{W_h^{1/3}} \quad (10-2)$$

This equation should be used for all blast holes in which the length of stemming exceeds the length of the charge. Several of the blasts, however, show a length of charge exceeding the length of stemming. In these cases, it is considered that only the length of charge equal to the length of stemming (S) is useful in producing rock breakage to the horizontal surface. In these cases, the minimum scaled depth of burial takes the following form:

$$B_s = \frac{3}{2} \frac{S^{2/3}}{w^{1/3}} \quad (10-3)$$

where w = Weight per lineal foot of charge

The effect of scaled depth of burial on overpressure amplitude was found to be significant. The analysis of the data shows that the overpressure can best be represented by an exponential function. The scaled propagation equation, corrected for scaled depth of burial, takes the form:

$$P = H e^{(-1.0 B_s)} \left(\frac{D}{W_d^{1/3}} \right)^{-n} \quad (10-4)$$

where P = Overpressure, psi

H = Pressure at a scaled distance
of unity for $B_s = 0$

e = Base of natural logarithm

n = Exponent (slope)

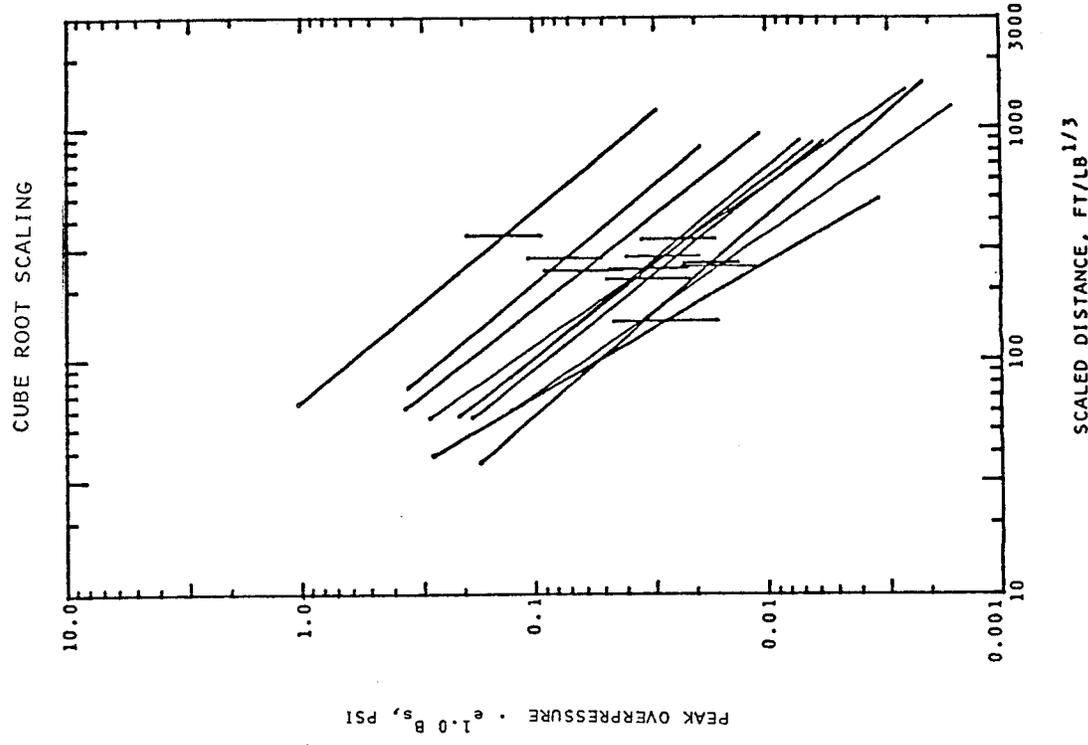


FIG. 10-1 - POSITIVE OVERPRESSURE UNCORRECTED FOR SCALED DEPTH OF BURIAL VS. SCALED DISTANCE, CONSOL, FABIOUS AND TEBO MINES

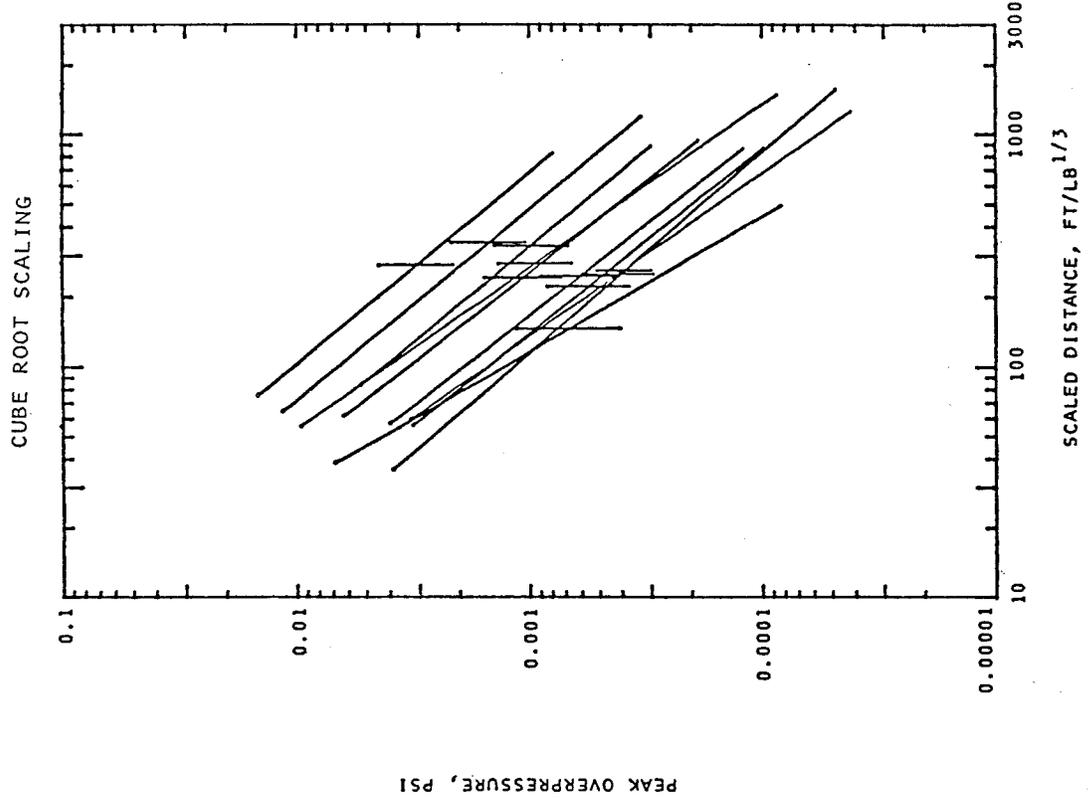


FIG. 10-2 - POSITIVE OVERPRESSURE, CORRECTED FOR SCALED DEPTH OF BURIAL, VS. SCALED DISTANCE, CONSOL, FABIOUS AND TEBO MINES

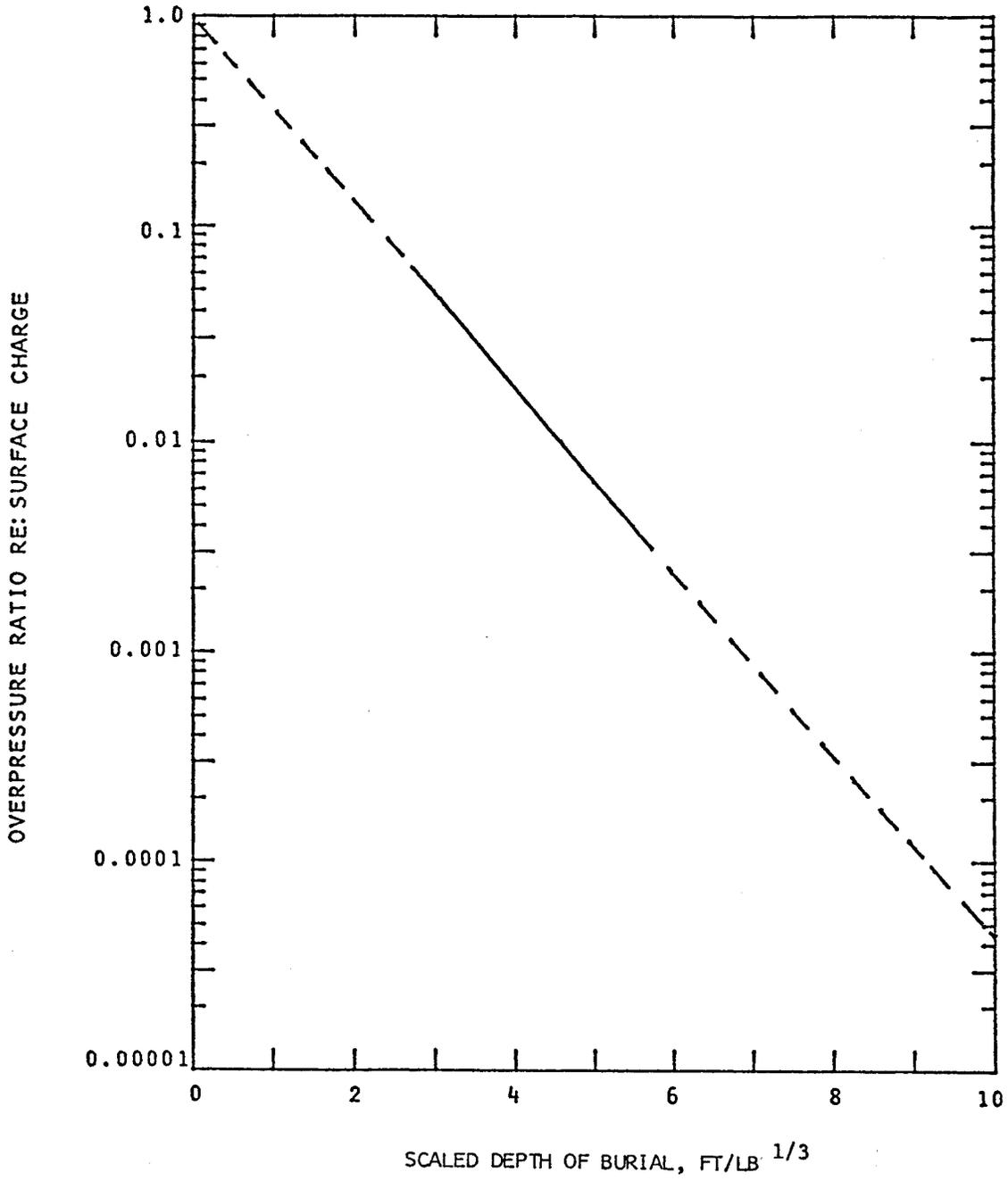


FIG. 10-3 - OVERPRESSURE RATIO VS. SCALED DEPTH OF BURIAL

regardless of whether the blast uses a deep hole or a satellite hole. Thus, both of these variables are eliminated during the subsequent simplification. The specific variables are limited to the scaled depth of burial and the maximum explosive weight per delay for both the deep and satellite holes, as well as the average positive or negative propagation slope which is independent of the hole depth.

Substitution of these variables into Eq. 10-5 allows a calculation for P_1/P_2 . If $P_1/P_2 > 1$, the maximum expected overpressure will result from the detonation in the deep hole. However, if $P_1/P_2 < 1$, the maximum expected overpressure will result from the detonation in the satellite hole. Thus, the statistical argument illustrated by Eq. 10-5 emphasizes an important consideration regarding the control of the expected overpressure using appreciably different depths of holes within a blast. The shallow holes which have a smaller charge size may result in an appreciably greater pressure amplitude since the scaled depth of burial is the dominating influence for the blast. If the blast uses uncovered detonating cord, the resulting overpressure should also be considered as a source of the peak amplitude. Chapter 18 of this report gives propagation laws for an instrument detector perpendicular to the line of the primacord.

Chapters 4-D-1, 5-H, and 5-I of the Technical Report gives the field experimental procedures, the data, and the detailed analyses developed during this investigation of charge depth.

The conclusions developed from this investigation can be summarized as follows:

1. The ground vibrations are not significantly affected by the scaled depth of burial.
2. The air vibrations are affected by the scaled depth of burial; as the scaled depth of burial increases, the resulting overpressure decreases. An exponential equation form can be used to quantify the relationship between the overpressure and the scaled depth of burial.
3. Vertical hole blasts which use deep holes as well as satellite holes should be evaluated to determine which type of hole will generate the maximum overpressure. The hole having the larger charge size does not necessarily develop the greater overpressure.

4. If the blast uses uncovered detonating cord, the resulting detonating cord overpressure should also be considered as a source of the peak amplitude.

CHAPTER 11 - CHARGE LENGTH AND DIAMETER

The effect of charge length and diameter on the amplitudes of ground and air vibration was studied by the scale-model tests. It was found that both of these parameters affected the amplitudes of the ground and air vibrations. However, the charge weight, regardless of its length and/or its diameter within the range of the parameters investigated, controlled the amplitudes. The length of the charge was varied by a factor of 4 and the diameter by a factor of 2.

Chapter 4-F of the Technical Report gives the test details and the analysis techniques used for this investigation.

CHAPTER 12 - LENGTH OF DELAY

This chapter discusses the effect of the length of the delay on the amplitude of the ground and air vibrations. For some of the blasts tested, either electric blasting caps or combinations of caps and a sequential timer were used. These tests resulted in several different delay intervals in a blast. Due to the inherent scatter in the timing of electric blasting caps, it was necessary to consider these blasts in terms of their nominal delay intervals.

For most of the blasts, either detonating cord connectors or instant caps in conjunction with the sequential timer were used. In these tests, the delay intervals used were either 9 ms, 10 ms, 17 ms, 33 ms, 58 ms, 100 ms, or 125 ms, and they were accurately controlled.

It was found from several experiments that the overpressure and seismic amplitudes can be affected by the length of the delay, the spacing of the blast hole, and the propagation velocity of the transmitting medium. The equation which demonstrates the inter-relationship of the parameters (see Appendix D-6 of the Technical Report) is of the form:

$$t_e = t_d - \frac{S \cos \phi}{C_m} \quad (12-1)$$

where t_e = Difference in arrival times of successive pulses at a given position
 t_d = Nominal delay between hole detonations
 S = Spacing between holes
 ϕ = Angle between successively detonated holes and position of interest
 C_m = Propagation velocity through the medium

Fig. 12-1 illustrates typical instrument positions and their relative firing angle ϕ for a blast layout of three holes in a single row. The firing sequence is also shown in the illustration. If the instrument position is directly in line with the row, as an example, with the detonation sequence towards the instrument position, then $\phi = 0^\circ$. The above equation is valid for far-field applications. When the difference in arrival time = 0, the pulses arrive simultaneously and maximum reinforcement occurs. Small differences in arrival time, which are less than the rise time of the pulse, will also produce reinforcement, although less than maximum. Differences in arrival times larger than the rise time of the pulse will not produce significant reinforcement.

An example of overpressure reinforcement can be demonstrated as follows. Assume a nominal delay (t_d) of 0.009 sec (9 ms), a hole spacing of 25 ft (S), an angle of the position of interest of 60° , and a propagation velocity in air of 1100 ft/sec (C_m). Substituting those values in Eq. 12-1 results in a difference in arrival times of successive pulses (t_e) as follows:

$$t_e = 0.009 - \frac{25 \cos 60^\circ}{1100} = 0.009 - 0.011 = - 0.002 \text{ sec}$$

Thus, the pulses arrive at the position of interest 2 ms apart, resulting in reinforcement of the overpressure, as the rise time of pressure pulses is usually 25 ms more or less.

The difference in arrival time of successive seismic pulses, assuming a propagation velocity of 8000 ft/sec, a hole spacing of 30 ft and the position of interest at 15° from the line of holes is:

$$t_e = 0.009 - \frac{30 \cos 15^\circ}{8000} = 0.009 - 0.004 = 0.005 \text{ sec}$$

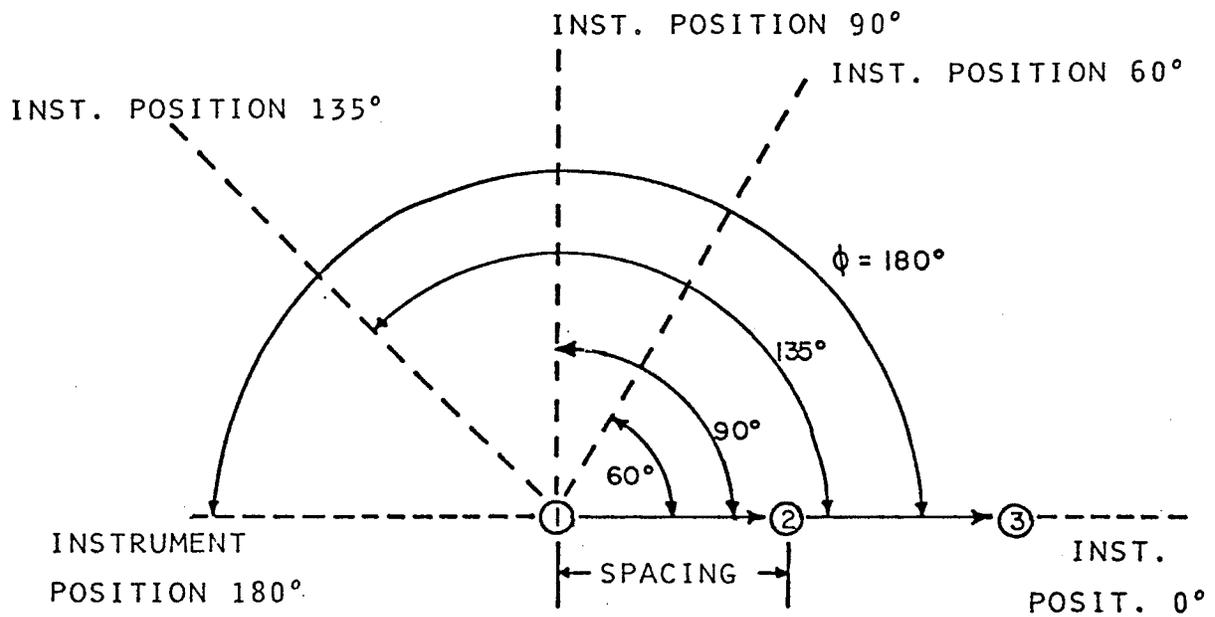


FIG. 12-1 - TYPICAL INSTRUMENT POSITIONS AND FIRING ANGLES FOR A 3 HOLE BLAST, WITH A FIRING SEQUENCE OF 1-2-3 FROM LEFT TO RIGHT

Thus, the pulses arrive at the position of interest 5 ms apart, probably resulting in some reinforcement of the ground vibration, as the rise time for seismic pulses is usually 10 ms, more or less.

The critical angle (ϕ_c) where maximum reinforcement occurs may be determined by setting $t_e = 0$ in Eq. 12-1. The equation then may be transformed to:

$$\phi_c = \arccos \frac{C_m t_d}{S} \quad (12-2)$$

Thus, the example given above for the overpressure results in a critical angle of

$$\phi_c = \arccos \frac{1100 (0.009)}{25} = 66.7^\circ$$

This angle is on both sides of the line connecting the successively detonated blast holes. If the length of the delay interval is changed to 0.017 sec (17 ms), the critical angle becomes 41.6° . Similarly, for a delay interval of 0.034 sec (34 ms), there will be no critical angle where reinforcing occurs.

Chapter 5-G and 5-J of the Technical Report gives the experimental procedures, test data, and analytical methods that provided the basis for this investigation.

The conclusions from this investigation can be summarized as follows:

1. The difference in the arrival time of successive pulses, t_e , is a significant variable for both the ground and air vibration. It is dependent on the interrelationship of several parameters. These include the blast delay interval, the hole spacing, the propagation velocity of the medium, and the location of the instrument position. As t_e approaches 0, phasing addition of the respective energy pulses can occur, with resulting reinforcement of the ground or air vibration.
2. The rise time of the seismic or overpressure pulse, resulting from the detonation of a charge, is a significant parameter that can affect the

amplitude of the ground and air vibration. If the rise time is greater than t_e , significant reinforcement can occur. If the rise time is less than t_e , significant reinforcement will probably not occur.

CHAPTER 13 - EFFECT OF RESONANCE WITH DELAY INTERVAL

It was the purpose of this investigation to determine if the delay interval, which matches the resonant ground frequencies observed from the seismographic records, results in appreciably higher amplitudes. The preliminary analysis of some of the early recordings at the site of this investigation indicated that the seismic frequencies were apparent in the range of 8 to 10 Hz, regardless of the delay interval. Subsequent blasts were therefore detonated with delay intervals of 100 and 125 ms, which would correspond to these seismic frequencies.

The analysis of the test data indicated that the seismic amplitudes showed no significant difference in relation to other blasts which use shorter delay intervals of 17 and 58 ms. There were variations of blast variables within the group of these blasts under evaluation, and some the records show lower seismic frequencies which may be ground resonant frequencies. However, on an overall basis, the analysis and data tend to support the conclusion that matching the delay interval with the resonant frequencies observed in the ground will not result in significant increases in the seismic amplitudes.

Chapter 5-G of the Technical Report gives the field experimental procedures, the test data, and the detailed analyses developed as a result of this investigation.

CHAPTER 14 - BURDEN AND SPACING

This chapter discusses the effects of the burden and spacing on the amplitudes of the ground and air vibrations. As previously illustrated, both the spacing and the delay interval between successively detonated blast holes determine the critical angle at which maximum reinforcing occurs. Depending on the sequence of detonation, the pertinent spacing of successive holes may be in the same row, or from the end of one row to the beginning of the next row.

Fig. 14-1 shows a blast pattern and geometry for the examples that follow. Assume a delay interval of 10 ms (t_d), a propagation velocity (C_m) for air of 1100 ft/sec, and for earth materials 8000 ft per sec. For overpressure, the critical angle (ϕ_c), where there is no difference between the arrival of successive pulses from blast holes in the same row spaced 25 ft, is determined by Eq. 12-2; thus:

$$\phi_c = \text{arc cos } \frac{1100 (0.010)}{25} = 63.9^\circ$$

The critical angle is on both sides of the line connecting successively detonated blast holes.

For the arrival of the pulses from Holes 4 and 5, when the burden is 25 ft, the critical angle is:

$$\phi_c = \text{arc cos } \frac{1100 (0.010)}{79} = 82.0^\circ$$

For a spacing of 30 ft and burden of 30 ft, the critical angle for blast holes in the same row is 68.5°, and between Holes 4 and 5, the critical angle is 83.3°.

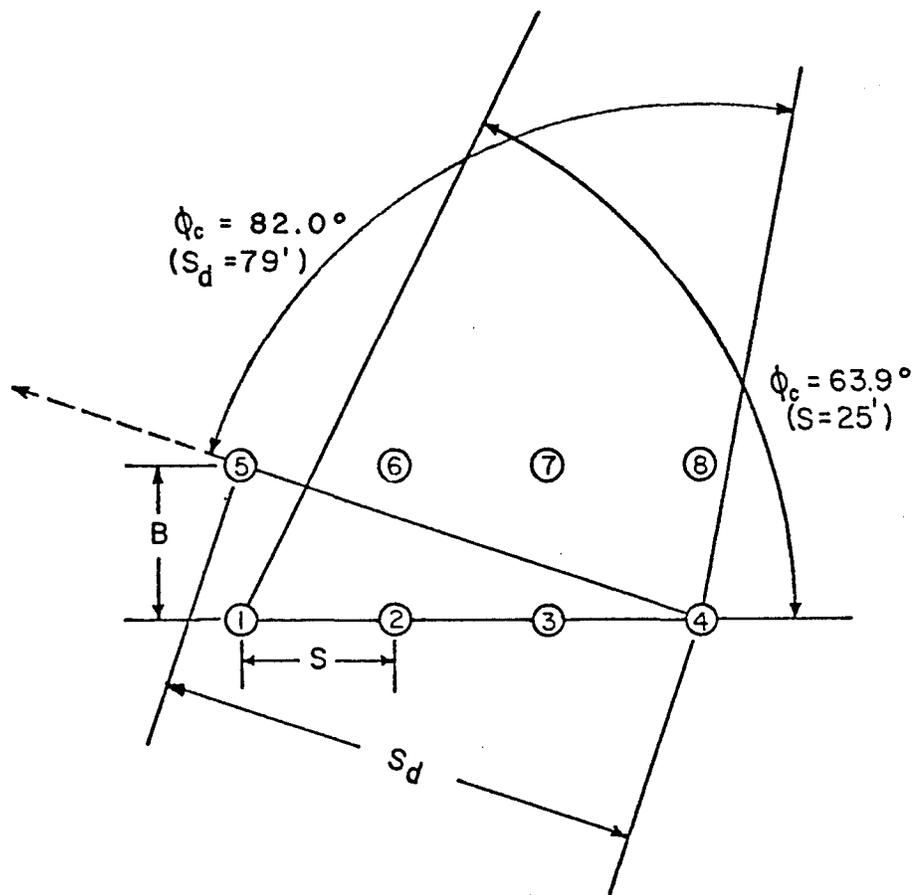
For the seismic effects, it is apparent by inspection of Eq. 12-1 that the shorter nominal delay intervals are most likely to produce a difference in arrival times that are sufficiently small to result in reinforcement. Further, due to the relatively higher propagation velocities through the earth medium, the spacing between successively detonated blast holes in the same row would have to be larger than are normally used in surface coal mines. For example, to result in a difference of arrival time (t_e) of 0, when using nominal delays of 10 ms (t_d) and assuming a $\cos \phi$ of 1.0 ($\phi = 0^\circ$), from Eq. 12-1

$$0 = 0.010 - \frac{S (1.0)}{8000}$$

it is apparent that the spacing between successively detonated holes would have to be 80 ft. However, some reinforcing will probably occur for differences of arrival times of 5 ms. Thus,

$$0.005 = 0.010 - \frac{S (1.0)}{8000}$$

and the required spacing (S) would be 40 ft.



SPACING (S) FT	BURDEN (B) FT	DIAGONAL SPACING (S _d) FT
25	25	79
30	30	95

FIG. 14-1 - BLAST PATTERN GEOMETRY AND CRITICAL ANGLES FOR EXAMPLE PROBLEMS (OVERPRESSURE)

With reference to the reinforcing between Blast Holes 4 and 5 in Fig. 14-1 for a spacing and burden of 25 ft, the critical angle from Eq. 12-2 will be

$$\phi_c = \text{arc cos } \frac{8000 (0.010)}{79} \approx 0^\circ$$

Thus, maximum reinforcement of the seismic pulses from Blast Holes 4 and 5 will occur in a direction indicated by the dashed arrow (on line with Holes 4 and 5).

Chapter 5-G and 5-J of the Technical Report describe the experiments and analytical techniques that provided the basis for this evaluation.

This investigation demonstrates that hole spacing is one of the factors that influences the effective delay interval t_e , and hence, the potential for reinforcement of the ground and air vibration in certain directions from the blast, as discussed in Chapter 12 of this report.

CHAPTER 15 - ATTITUDE (ANGLE OF BOREHOLE)

This chapter discusses the effects of the attitude of the borehole on the amplitudes of the ground and air vibration. During the scale-model tests, individual blast holes with three attitudes were detonated. These included vertical, diagonal (45°), and horizontal holes. During the experimental tests at the surface mine, production blasts using either vertical or horizontal holes were detonated.

Chapters 4-E and 5-H of the Technical Report gives the field experimental procedures, the test data, and the detailed analyses developed during this investigation.

The results of both test series indicate that there was no significant difference in the amplitudes of the ground or air vibration from vertical or horizontal blast holes which had (or were corrected for) the same scaled depth of burial. Although the scale-model tests indicate slightly higher amplitudes for the diagonal holes, such differences are not significant, and it is concluded that the attitude of the blast hole did not affect the ground or air amplitudes.

CHAPTER 16 - DIRECTIONAL EFFECTS

The effects of the direction of the blast on the amplitudes of the ground and air vibration is discussed herein. Experimental tests of production blasts at the mines were made using instrument arrays in different directions. Blasts utilizing a single row of horizontal holes were used for these tests. The instruments were on a line perpendicular to the row of blast holes, and parallel to the row. For the latter tests, the blast holes were detonated toward the instrument array and away from the instrument array.

The analysis of the data shows that there is a significant difference as a result of the direction of the blast. When the instrument array was located perpendicular to the firing pattern, the seismic and overpressure amplitudes were approximately 2 to 2 1/2 times as large as firing away from the parallel instrument array. The greatest seismic and overpressure amplitudes were observed when the blasts were fired toward the instrument array. The seismic and overpressure amplitudes for this condition were approximately 3 to 6 times as large as firing away from the instrument array.

These blasts used a delay interval of 9 ms between holes. By the techniques described in Chapter 12 (Length of Delay) of this report, it can be shown that a decrease of the effective delay or difference in arrival times of the pulses resulted in an increase in seismic or overpressure amplitudes due to phasing addition. Conversely, an increase in the effective delay (or difference in arrival times) resulted in a decrease in seismic or overpressure amplitudes.

It is considered that at this mine an increase to 17 ms delay intervals would most likely eliminate the phasing addition with direction for the seismic data, but would still leave the phasing addition problem in the overpressure data. For a 30-ft spacing of blast holes, the delay interval would probably have to be at least 50 ms to fully eliminate the phasing addition problem with direction for the pressure data.

Chapter 5-J of the Technical Report describes the experiment and analytical techniques used for this investigation.

This experiment demonstrates that the direction of initiation of the blast influences the effective delay interval t_e , and hence, the potential for reinforcement of the ground and air vibration in certain directions, as discussed in Chapter 12 of this report.

CHAPTER 17 - STEMMING

This chapter discusses the effects of the stemming on the amplitudes of the ground and air vibration. The scale-model tests were designed with various amounts and sizes of stemming material while the depth to the center of gravity of the charge was held constant. The shot holes were 3 1/2 inch diameter and the stemming material was stone sand, stone chips (1/4 to 3/8 in.), and stone (1/2 to 3/4 in.).

The test results indicate that the stemming length and size have no effect upon the amplitudes of the seismic data. As might be expected from this observation, it was also found that the length or size of stemming had no effect on the amplitudes of the Air Pressure Pulse (APP) generated by the vertical ground motion in the proximity of the blast hole.

The Stemming Release Pulse (SRP) generated by the blowout of the stemming and the escaping gas from the borehole increased in amplitude as the stemming length decreased. The amplitude of the SRP followed a negative exponential relationship with respect to the length of stemming. For a given distance, charge weight, and depth of charge, this relationship may be represented as an equation of the form:

$$p = k e^{-aS} \quad (17-1)$$

where p = Overpressure
 k = Intercept
 e = Base of natural logarithm
 a = Coefficient of S
 S = Length of stemming

Eq. 17-1 has the same form which was found to be most appropriate for the effects of the depth of burial on the APP. For the scale-model tests, the length of the stemming S is replaced by the depth to the center of gravity of charge D_{cg} .

Chapter 4-D-3 of the Technical Report gives the field experimental procedure, the test data, and the detailed analyses developed for this investigation.

Although controlled experiments on stemming length were not conducted at the surface mines, certain observations were made from

available data. It was found that in many cases when there was evidence of minor stemming blowouts, the overpressures were not significantly increased; the SRP was not identifiable in the complex overpressure waveforms resulting from delayed multi-hole blasts. At the time that major blowouts occurred during a blast, the overpressures ranged from 3 to 8 times the maximum overpressure that occurred during the remainder of the blast recording. Such blowouts involved more than the stemming release; they resulted in considerable throw of the earth materials.

The conclusions from this investigation can be summarized as follows:

1. The ground vibrations are not significantly affected by the length or size of the stemming.
2. The stemming release pulse (SRP) is affected by the length of stemming above the charge; as the length of the stemming increases, the SRP decreases. An exponential equation form can be used to quantify this relationship.

CHAPTER 18 - BARE VS. COVERED DETONATING CORD

This chapter discusses the effects of bare and covered detonating cord during the scale-model tests. The range of lengths of the detonating cord was from 2 to 40 ft, and two sizes of detonating cord were used, 5 and 50 grains of explosive per ft. For one series of tests, 20-ft lengths of both sizes of detonating cord were tested when the depth of stone sand cover was 3, 6, and 12 in. For all the tests except one, the instrument array was perpendicular to the line of detonating cord at its center. For one test using a 20-ft length of 50 grain/ft detonating cord, the line of the detonating cord was parallel to the instrument array, and the detonation direction was toward the instrument array.

It was found from these tests that larger pressures were generated when the detonating cord was at right angles to the instrument array than when it was parallel by factors of 9 and 16 for the positive and negative pressures, respectively. It was also found that the overpressure was a function of the square root of the equivalent charge weight of the length of detonating cord when the line of detonating cord was perpendicular to the instrument array. The propagation equations for the pressures generated by the detonation of various lengths of detonating cord up to 40 ft are:

$$P_+ = 158 \left(D/W^{0.5} \right)^{-1.188} \quad (18-1)$$

$$P_- = 12.2 \left(D/W^{0.5} \right)^{-0.843} \quad (18-2)$$

In these equations, the distance D is in ft, charge weight W is in lbs, and pressure P is in psi.

Covering detonating cord is very effective in reducing the level of overpressure generated. For the 50-grain detonating cord, the level of air pressures generated was reduced by a factor of 10, with just 3 in. of sand cover, and by nearly 100 for 12 in. of sand cover.

The spectral analysis of the data revealed that the predominant frequency component for the uncovered detonating cord, as recorded perpendicular to the line of detonating cord, decreased as the equivalent charge weight increased. The predominant frequency for 2 ft of 5-grain detonating cord (0.0021 lbs) was 350 Hz. For 40 ft of 50-grain detonating cord (0.2864 lbs), the predominant frequency was 100 Hz.

The effect of cover for 20 ft of 50-grain detonating cord (0.1436 lbs) was to reduce the predominant frequency from the uncovered detonating cord from 100 Hz to 65 Hz for the covered detonating cord.

Chapter 4-D-2 of the Technical Report discusses the experiment and analytical techniques used for this investigation.

The conclusions for this investigation can be summarized as follows:

1. A power equation form with a square root scaling law can be used to quantify the relationship between resulting overpressure and the charge weight of the detonating cord. This relationship is valid when the detonating cord is perpendicular to the instrument location.
2. When the detonating cord was parallel to instrument position, as compared to perpendicular to the instrument position, the resulting overpressure was approximately one order of magnitude smaller.
3. The use of cover over the detonating cord is very effective in reducing the level of the overpressure.

4. The spectral analysis of the overpressure records showed a correlation between the overpressure and the charge weight of the detonating cord. An increase in the charge weight of the detonating cord resulted in a decrease of the dominant spectral frequency.

CHAPTER 19 - SURFACE WINDS

The effects of surface winds on the overpressure was investigated from the data available at the sites with relatively flat terrains and comparable light foliage. The wind speed vector that was pertinent to this evaluation was with respect to the instrument array. A wind from the direction of the blast, down the instrument array, was assigned an angle of 0° . Other wind angles, ϕ , are measured clockwise from the 0° direction. Hence, the vector velocity, U_v , with respect to the instrument array for any wind speed, U , may be calculated from the following equation:

$$U_v = U \cos \phi \quad (19-1)$$

The propagation slopes for individual blasts were examined in relation to the vector wind velocity. A plot of the propagation slopes vs. vector wind velocity on rectilinear paper suggested a straight line correlation for winds up to approximately 20 mph. A statistical analysis of the data revealed that the average slope (n) of the propagation equation for overpressures as a function of vector wind speed (U_v) was

$$n = 1.2734 - 0.0265 U_v \quad (19-2)$$

Hence, for a vector wind speed of 0, the slope of the propagation equation is 1.2734. A vector wind speed of U_v (mph) from the blast down the instrument array will reduce the slope by $0.0265 U_v$. A vector wind speed of U_v along the array toward the blast will increase the slope of the overpressure propagation equation by $0.0265 U_v$.

In terms of dB, these overpressures correspond to a decrease of approximately 8 dB per double distance for a vector wind velocity of 0 mph. Further, for each 5-mph increment of vector wind speed from the blast down the instrument array, there will be a decrease of approximately 1 dB per double distance. Conversely, an increase in attenuation of approximately 1 dB per 5-mph increment of wind

vector wind speed will result when the wind is along the array toward the blast.

Chapter 5-K of the Technical Report gives the detailed analyses developed for this investigation.

The conclusions from this investigation can be summarized as follows:

1. The surface wind is a significant variable which affects the measured overpressure at a gage position.
2. The effects on the propagation slope of the surface wind can be quantified having a linear equation form. A vector wind speed from the blast down the instrument array reduces the propagation slope. Conversely, a vector wind from the instrument array toward the blast increases the propagation slope.

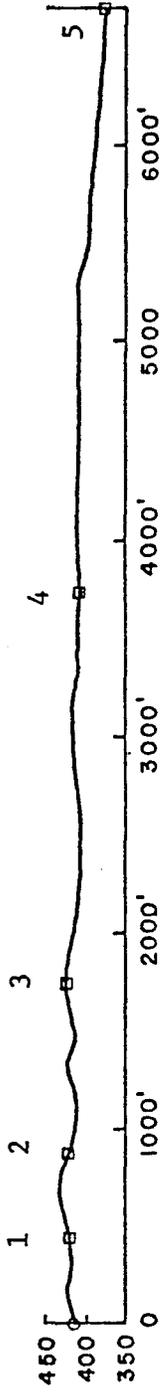
CHAPTER 20 - SURFACE TERRAIN

The effects of surface terrain on the overpressure amplitudes were investigated at Sahara, Tebo 1 and Tebo 2, at which sites the instrument array was identical for all the blasts at the site. The slopes of the distance propagation equations for the individual blasts were corrected to a 0 vector wind velocity by the method described in the previous section. An average of the corrected slopes was then examined with respect to the individual terrain at the sites.

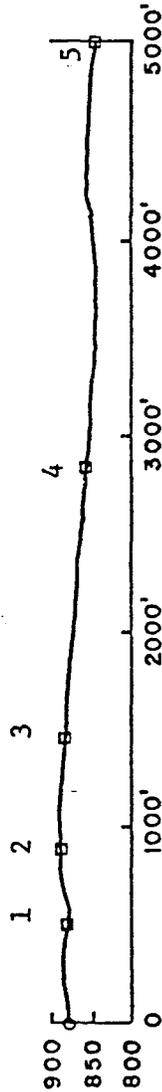
The terrain at all of the sites was relatively flat and the foliage was comparable between sites. The corrected average slopes were 1.206 for Sahara, 1.433 for Tebo 1, and 1.171 for Tebo 2. The variation in elevations for the sites is shown in Fig. 20-1.

The differences in the corrected average slopes, although not large, cannot be correlated with the variations in the terrain. Further, the propagation slopes from individual blasts at the same site, when corrected for wind, covered a wide range, which indicates that the terrain is not a significant factor in establishing the slope of the propagation equation for the overpressure; i.e., the attenuation of overpressure with distance.

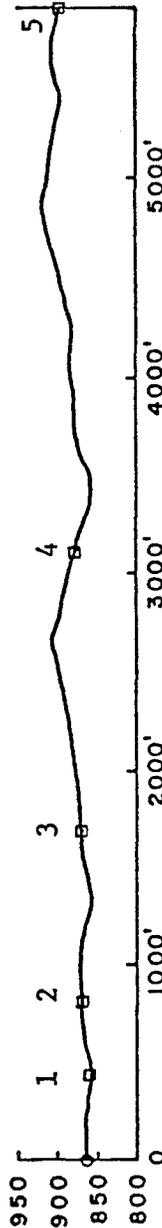
This does not imply that extremes in terrain, which were greater than those which existed at the test sites, would not affect the slope of the propagation equation. It does appear, however, that other factors which were not apparent have a greater influence than terrain.



SAHARA MINE - FEBRUARY 1976



TEBO MINE (T1) - APRIL 1976



TEBO MINE (T2) - AUGUST 1976

○ BLAST LOCATION
 □ INSTRUMENT POSITION

FIG. 20-1 - SURFACE TERRAIN PROFILES ALONG INSTRUMENT ARRAY

These may include temperature gradients, local turbulence, or higher altitude conditions that were not observed or recorded during these tests.

Chapter 5-1 of the Technical Report presents data used in this evaluation.

CHAPTER 21 - TYPE OF OVERBURDEN

The type of overburden in the blast area does affect the amplitudes of the seismic and the overpressure pulses. This is apparent from the difference in the intercepts for the scaled-distance propagation equations. Although the slopes of the propagation equations affect the intercepts, with the exception of one site, the slopes are not sufficiently different to significantly affect the intercepts.

Since shale is common to all sites, it appears that the overburden which contained sandstone strata produced less ground vibration than those which contained limestone strata. The overburden composition in the blast area also generally appears to similarly affect the overpressure.

The overburden along the instrument array affects the slope of the seismic propagation law. The nature of the overburden (as observed in the vicinity of the highwall) indicates that considerable stratification in the overburden results in a greater propagation slope than thick ledges with little laminations. In general, a representative average slope for the seismic propagation equation at all of the sites is approximately 1.5. One of the notable exceptions is the surface mine which is located above an area with extensive underground mining. The slope of the seismic propagation equation at this mine is approximately 1.7.

CHAPTER 22 - REINFORCING OF OVERPRESSURES FROM MILLISECOND DELAY BLASTS

This chapter discusses the effects of reinforcing of overpressures from millisecond delay blasts on the amplitude of the air vibration.

Several of the overpressure records obtained during the study on the effects of the delay interval, show fewer pulses at certain gage locations than were expected in view of the number of holes detonated in the millisecond delay blast. Further, the amplitudes

of some of the pressure pulses were larger than others in the blast. These anomalies prompted an investigation of the reasons for their occurrence.

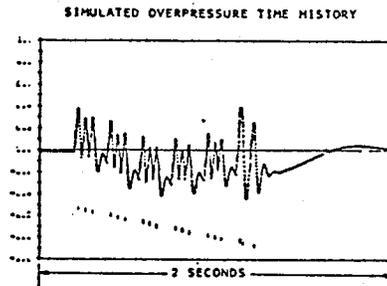
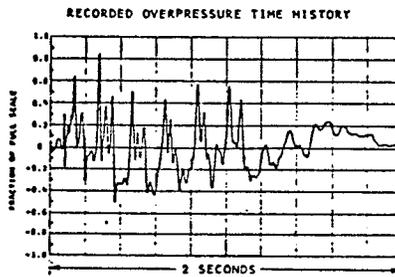
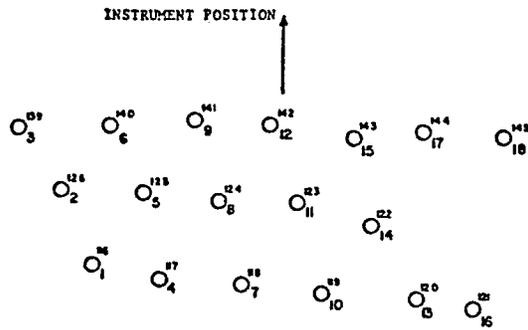
A computer program was developed to simulate pressure time histories of multiple-hole delayed blasts, using a simple arrival-time equation; the coordinates of the instrument position and hole locations of the blast; and an equation which simulated the pressure time history of a single-hole blast. The detonation of a single-hole charge has many interactive effects, which ultimately result in variations of the pressure time history. However, on the basis of the initial evaluations, good correlation was obtained between the computer simulation and the actual pressure time histories, using an exponentially damped sinusoidal equation series limited to a maximum of three terms.

The pressure time simulation for a blast which consisted of 18 holes/18 delays at 58 ms, is shown in Fig. 22-1. The figure also shows the blast hole layout and firing sequence, the actual record pressure time history at the instrument position, the calculated arrival time of the peak amplitude for each hole, and the calculated effective delay which is a relative arrival time of the peak amplitudes. Good correlation between the actual pressure time history and the simulation is evident, although the simulation did not result in predicting which two holes would give maximum reinforcement.

The analysis of several blasts from two different sites also shows that the simulation of the pressure time histories is feasible with a computer application. There were some apparent differences for some of these analyses; however, the computer simulation emphasized the importance of two parameters in estimating the peak overpressure amplitude resulting from phasing addition of the energy pulses. These are the difference in the arrival time of the successive pulses, which can be quantified using Eq. 12-1 given in Chapter 12 of this report, and the character of a single-hole detonation pressure pulse.

The limited amount of single-hole pulse test data which was available shows that there are variations in the single-hole waveform pressure time history, which is attributable to several factors, including the difference in geology, and the depth of the charge. However, even with these variations, good correlation was generally obtained using a simulation technique. Thus, the more important factor in determining the peak overpressure apparently is the relative arrival time of the pulses.

The simulation study also shows that this technique does not require a complex type of computer or computer program. An exponentially damped sine equation having three terms was used to give



<u>HOLE NO.</u>	<u>ARRIVAL TIME OF PEAK AMPLITUDE(SEC)</u>	<u>EFFECTIVE DELAY(SEC)</u>
116	1.302	
126	1.340	0.038
139	1.381	0.041
117	1.483	0.102
125	1.520	0.037
140	1.561	0.040
118	1.664	0.103
124	1.702	0.038
141	1.739	0.037
119	1.846	0.107
123	1.882	0.035
142	1.919	0.038
120	2.029	0.110
122	2.066	0.037
143	2.103	0.037
121	2.209	0.106
144	2.223	0.014
145	2.288	0.066

FIG. 22-1 - COMPARISON OF RECORDED OVERPRESSURE TIME HISTORY WITH SIMULATION, BLAST F5L

maximum simulation. However, the analysis also shows that reasonably good correlation was obtained using two terms of the equation.

Chapter 5-M of the Technical Report gives the field experimental procedure, the test data, and the detailed analyses developed for this investigation.

The conclusions developed from this investigation can be summarized as follows:

1. Computer computational techniques to simulate the expected overpressure from a blast is a feasible approach which does not require complex hardware, or complex programming. This technique should reduce the error associated with estimating the peak overpressure, as well as provide a basis for designing blasts which minimize the overpressure amplitude.
2. The two significant parameters for giving adequate simulation, using the computer technique, are the difference in the arrival time of successively detonated pressure pulses and the character of the pressure pulse expected from a single-hole detonation. The difference in the arrival time of successively detonated holes appears to be the more important of the two parameters.

CHAPTER 23 - FREQUENCY COMPOSITION OF GROUND AND AIR VIBRATION

The frequency composition of the ground vibration was generally characteristic of the terrain for those blasts that used short delay intervals. The predominant frequencies ranged from 5 to 20 Hz, with the lower frequencies associated with the deeper soil overburden (20 ft), and the higher frequencies associated with thinner soil (7-10 ft). For comparable thicknesses of soil overburden, underlying strata of limestone resulted in higher frequencies than sandstone. In general, the predominant frequencies decreased with distance from the blast. This is due to the absorption of the higher frequencies in the transmitting medium.

For the blasts that utilized delay intervals of 17 ms or greater, the frequencies corresponding to the delay interval were also apparent in the frequency spectrum. The greater the number of delays at a particular interval, the greater the spectral amplitudes at the corresponding frequencies.

The predominant spectral frequency in the overpressure recordings were generally approximately 1 Hz. The use of long delay intervals in the blasts (i.e., 60 ms) also resulted in significant spectral amplitudes at the corresponding frequencies.

CHAPTER 24 - RECOMMENDATIONS

In order to minimize the seismic vibration at a particular site, the following procedures should be followed:

1. Minimize the maximum explosive weight per delay
2. Avoid short delay periods. Delay intervals of 17 ms or more should minimize any increase in vibration (phasing) with direction
3. Select spacing of blast holes, delay intervals, and sequence of firing to avoid reinforcing in critical directions

To minimize air blast noise at a particular site, the following procedures should be followed:

1. Minimize the maximum explosive weight per delay
2. Maintain maximum possible charge depth
3. Select spacing and burden of blast holes, delay intervals, and firing sequence to avoid reinforcing in critical directions
4. Use maximum possible stemming and coarse angular stemming material
5. Cover detonating cord with at least 3 in. (preferably 12 in.) of cover
6. Avoid blasting when wind is in critical directions from the blast

Without instrumentation, and based on cube root scaling, a scaled distance of 300 should produce a peak particle velocity of less than 1 ips. For square root scaling, a scaled distance of 75 will limit the ground vibration to less than 1 ips. An overpressure of 128 dB linear peak will probably not be exceeded for a scaled distance of 300 based on cube root scaling.

The above scaled distances are conservative since they are based on two standard deviations above the mean line for the highest propagation equation for any of the mines. Limiting scaled distances significantly less than those reported above will very likely result when based on instrumented tests to establish the scaling factor and propagation equation for both the ground and air vibrations at a particular site.