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TECHNICAL REPORT E-73-1.

PROJECT TRINIDAD
EXPLOSIVE EXCAVATION TESTS IN
SANDSTONE AND SHALE

Bruce B. Redpath

July 1972
(Revised)

MASTER

U.S. Army Engineer Waterways Experiment Station
Explosive Excavation Research Laboratory
Livermore, California

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BRUCE B. REDPATH

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Foreword

The Explosive Excavation Research Laboratory (EERL)* is embarked on a program of research in topical areas critical to the overall technology that is referred to as "explosive excavation." This is the report of a complete program of explosive excavation experiments, and includes summaries of the related technical programs such as seismic effects, airblast generation, and engineering properties of a large crater excavated for a railway cut. The report is primarily oriented towards the cratering aspects of the program, for indeed, the acquisition of the cratering characteristics of a weak rock and the verification of row-charge design rules were the principal goals in conducting the experiments. The excavation of a railway cut at the conclusion of the project was a successful demonstration of the economic benefits of explosive excavation. Two additional railway cuts later excavated in the same area represented immediate and beneficial applications of the knowledge acquired during the project, and this same knowledge will continue to contribute to the mission of EERL.

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*The U. S. Army Engineer Waterways Experiment Station (USAEWES) Explosive Excavation Research Laboratory (EERL) was the USAEWES Explosive Excavation Research Office (EERO) from 1 August 1971 to 21 April 1972. Prior to that time, it was known as the USAE Nuclear Cratering Group (NCG).

Abstract

A series of single-, row-, and multiple-charge cratering detonations, with individual charge weights of 1 to 2 tons, were carried out in weakly interbedded sandstones and shales near Trinidad, Colorado, in 1970 and 1971. The principal objectives of these excavation experiments were to obtain single-charge cratering curves, to verify row-charge designs for achieving a specified excavation, to determine the effects of millisecond delays in row-charge cratering, to experiment with cratering in varying terrain, and to compare the cratering effectiveness of several explosives. Three varieties of aluminized ammonium-nitrate blasting agents and ANFO were used. Airblast and seismic effects of each detonation were monitored. The series culminated with the excavation of a railway cut 400 ft long with 44 tons of explosives distributed among 32 charges.

Acknowledgments

This report is the outcome of the efforts of many people involved in Project Trinidad. LT Terry Shackelford wrote Chapter 2 and, together with MAJ Charles Gardner, also wrote Chapter 6; LT Dale McWilliams contributed significantly to Chapter 4; and Charles Snell prepared Chapter 5. MAJ Richard Gillespie was Test Director. The Albuquerque Engineer District provided outstanding contractual and operational support throughout the project. Messrs. Wayne McIntosh and Victor Hensinger of the Albuquerque District contributed significantly to the efficient accomplishment of the experimental program. All of the people above were responsible for the successful conduct of their respective technical programs in the field, and to them is due the credit for the overall success of the project.

Appendix E was written by Prof. J. M. Duncan and Mr. C. K. Chan of the University of California, Berkeley; this work was performed by Prof. Duncan and Mr. Chan under contract DACW07-71-C-0032 with the University of California, Berkeley.

COL William E. Vandenberg, LTC Robert L. LaFrenz, and LTC Robert R. Mills, Jr. were Directors of EERL during the course of the field work and the preparation of this report.

Contents

FOREWORD	ii
ABSTRACT	iii
ACKNOWLEDGMENTS	iv
CONVERSION FACTORS	x
CHAPTER 1. INTRODUCTION	1
General	1
Background and Objectives	1
Scope of Program	2
Project Organization	4
CHAPTER 2. SITE DESCRIPTION	4
Location and Topography	4
Geology	5
Preshot Engineering Properties of Site Medium	6
CHAPTER 3. CRATER MEASUREMENTS	7
B-Series	8
C-Series	12
Simultaneous Rows (C1, C2, C3)	13
Delayed Row-Charges (C4, C5)	17
Double Row-Charge Detonation (C6)	17
D-Series	18
Single Row-Charge through Varying Terrain (D1)	18
Single Row-Charge along a Sidehill (D2)	23
Double Row-Charge along a Sidehill (D3)	25
Delayed Double Row-Charge (Railway Cut, D4)	27
CHAPTER 4. SEISMIC MEASUREMENTS	32
Scope	32
Results	35
CHAPTER 5. AIRBLAST MEASUREMENTS	36
Scope	36
Results	37
CHAPTER 6. ENGINEERING STUDIES OF D4 CRATER	39
Introduction	39
On-Site Investigative Programs	39
Mass Density and Bulking Factor	39
Field Determination of Particle Gradation	39
Drilling, Coring, and Borehole Photography	40
Shaping of Railroad Cut	41
Fallback Compaction and Field Settlement Study	42

CHAPTER 7. CONCLUSIONS	44
APPENDIX A DRILL HOLE LOCATIONS, STRATIGRAPHY AND LITHOLOGY, AND MATERIAL PROPERTIES DATA	47
APPENDIX B CRATER PROFILES AND CROSS SECTIONS	54
APPENDIX C SEISMIC DATA	62
APPENDIX D AIRBLAST DATA	65
APPENDIX E LABORATORY TESTING OF FALLBACK MATERIAL	78
REFERENCES	92
FIGURES	
1. Organization of Project Trinidad	3
2. Project Trinidad site location	4
3. Generalized stratigraphic section of Trinidad, Vermejo, and Raton formations	5
4. Engineering classification for intact rock	7
5. Aerial view of principal experimental area showing B series, C series, and D4 crater	8
6. Bucket auger used to emplace charges	10
7. Typical 1-ton single-charge crater	10
8. Apparent crater radii and depths for B series	10
9. Volumes of B series apparent craters	10
10. C3 row crater	15
11. Row crater enhancement vs charge spacing	15
12. Single-charge cratering curves with row crater dimensions superimposed	16
13. Longitudinal profiles, charge layout, and cross sections of C6 crater	19
14. D1 preshot terrain, charge layout, cross sections, and crater profile	21
15. D1 crater	22
16. Longitudinal profiles and cross sections of D2 crater	24
17. D2 crater	25
18. Longitudinal profiles and cross sections of D3 crater	26
19. D3 crater	26
20. Anticipated cross section and plan view of D4 experiment	28
21. Chart of charge spacing vs depth of cut for 1- and 2-ton charges of TD-2 slurry in sandstone and shale	28
22. D4 detonation	29
23. D4 crater viewed from west to east along center line of railroad	29
24. Cross sections of D4 railway cut showing comparison between crater and cut excavated by conventional methods	31
25. Locations of seismic monitoring stations during Project Trinidad	32
26. Peak ground motion amplitudes vs distance	34
27. Peak airblast overpressures for selected Project Trinidad detonations	38

28. Map of D4 crater showing location of postshot engineering investigations	40
29. Location of core holes in D4 crater and extent of blast-induced fracturing (cross section through Station 93+00)	41
30. Dozer daylighting end of cut and bringing cut to grade	41
31. Dozer scales crater slopes; front loader removes material from crater	42
32. Finished cut	42
33. Settlement markers	42
34. Layout of settlement markers for vibratory compaction tests	43
35. Bros smooth-roller vibratory compactor	43
36. Surface settlement produced by vibratory compaction tests	44
A1. Map showing location of core holes for B and C series and D4 railroad cut	47
A2. Map showing location of emplacement and core holes for Experiment D1, D2, and D3	48
A3. Stratigraphy and lithology of B series	49
A4. Stratigraphy and lithology of C series	49
A5. Stratigraphy and lithology of Experiments D1, D2, and D3	50
A6. Stratigraphy and lithology of D4 railroad cut	50
B1. Crater nomenclature	54
B2. Cross sections of craters B1 and B2	55
B3. Cross sections of Craters B3 and B4	56
B4. Cross sections of Craters B5 and B6	57
B5. Cross sections of Craters B7 and B8	58
B6. Longitudinal profiles and representative cross sections for Rows C1 and C2	59
B7. Longitudinal profiles and representative cross sections for Row C3	60
B8. Longitudinal profiles and representative cross sections for Rows C4 and C5	61
D1. Observed single-charge transmission factors as a function of scaled depth of burst for aluminized ammonium nitrate slurry detonations, Project Trinidad	72
E1. Comparison of grain-size distribution curves determined by point count technique and by sieving	79
E2. Grain-size distribution curves for material as received and for test specimens	80
E3. Variations of maximum and minimum density with maximum particle size	81
E4. Wet specimen (36-in. diameter) after testing	82
E5. Stress-strain and volume change curves for specimens compacted to 71% relative density (confining pressure, 15 psi)	83
E6. Stress-strain and volume change curves for specimens compacted to 71% relative density (confining pressure, 30 psi)	83

E7. Stress-strain and volume change curves for specimens compacted to 77% relative density (confining pressure, 15 psi)	83
E8. Stress-strain and volume change curves for specimens compacted to 77% relative density (confining pressure, 30 psi)	84
E9. Stress-strain and volume change curves for specimens compacted to 73% relative density (confining pressure, 15, psi)	84
E10. Stress-strain and volume change curves for specimens compacted to 73% relative density (confining pressure, 30, psi)	84
E11. Stress-strain and volume change curves for specimens compacted to three relative densities (confining pressure, 15 psi)	85
E12. Stress-strain and volume change curves for specimens compacted to three relative densities (confining pressure, 30 psi)	85
E13. Compression time curves for specimens compacted to 80% relative density	86
E14. One-dimensional compression curves for specimens compacted to 80% relative density	86
E15. One-dimensional compression curves for specimens compacted to 50% relative density	87
E16. Variations of angle of internal friction with relative density	90
E17. Variation of volumetric strain due to wetting with maximum particle size	90
E18. Variation of compression due to wetting with overburden pressure for at-rest pressure conditions	91

TABLES

1. Summary of Project Trinidad cratering experiments	2
2. B-series cratering charges	9
3. Characteristics of Project Trinidad explosives	11
4. B-series crater dimensions	12
5. C-series charge emplacement	14
6. Summary of row crater dimensions	15
7. Unit volumes for C-series row craters	16
8. Summary of D-series experiments	20
9. D1, D2, D3 charge emplacement	22
10. D4 charge emplacement summary	30
11. Locations of seismic recorders, Project Trinidad	33
12. Airblast damage criteria	38
A1. Results of tests of B-series rock cores	51
A2. Results of tests of C-series rock cores	52
A3. Results of tests of D-series rock cores	53

C1. Maximum recorded particle velocities for B-series	62
C2. Maximum recorded particle velocities for C1, C2, C3	62
C3. Maximum recorded particle velocities for C4, C5, C6	63
C4. Maximum recorded particle velocities for D-series	64
D1. Close-in airblast observations for Detonations B1 through B8 (single-charges). Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar	65
D2a. Close-in airblast observations for Detonations C1 and C2 (row-charges). Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar	66
D2b. Close-in airblast observations for Detonations C3 and C4 (row-charges). Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar	67
D2c. Close-in airblast observations for Detonations C5 and C6 (row-charges). Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar	68
D3. Close-in airblast observations for Detonations D1 through D3 (row-charges). Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar	69
D4. Close-in airblast observations for Detonation D4 (row-charges). Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar	70
D5a. Ground-shock-induced overpressure reinforcement correction factors for Trinidad row-charge detonations	73
D5b. Gas-vent-induced overpressure reinforcement correction factors for Trinidad row-charge detonations	74
D6. Airblast amplitudes for row-charges expressed in terms of single-charge airblast amplitudes	76
E1. Composition and specific gravities of various sized fractions of Trinidad fallback	80
E2. Values of particle breakage factor B determined by resieving triaxial specimens after testing	87
E3. Summary of triaxial test results	89
E4. Surface settlements due to groundwater rise within 5 ft of ground surface for various fallback layer thicknesses	91

Conversion Factors

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
cubic feet	0.02832	cubic meters
cubic yards	0.764555	cubic meters
pounds	0.4535924	kilograms
pounds per square inch	0.00689476	meganewtons per square meter
pounds per cubic foot	16.02	kilograms per cubic meter
Fahrenheit degrees	5/9	Celsius or Kelvin degrees ^a
foot-pounds	0.138255	meter-kilograms

^aTo obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

TECHNICAL REPORT E-73-1

PROJECT TRINIDAD

EXPLOSIVE EXCAVATION TESTS IN SANDSTONE AND SHALE

Chapter 1. Introduction

GENERAL

This report is a technical summary of the results of an extensive series of excavation experiments conducted in interbedded sandstones and shales near Trinidad, Colorado. The experimental program progressed from single-charge craters through row-charge craters to multiple row-charge detonations. The individual charge weights were of the order of 1 ton, and a variety of explosives were used. Project Trinidad was conducted by the U.S. Army Corps of Engineers Waterways Experiment Station Explosive Excavation Research Laboratory (EERL). At the time of the experiments, in the summer and fall of 1970, the organization was known as The Nuclear Cratering Group (NCG). The Nuclear Cratering Group was organized in 1962 to engage in a joint venture with the AEC to investigate peaceful excavation applications of nuclear explosives.

BACKGROUND AND OBJECTIVES

All of the early cratering experiments performed by EERL were designed as chemical-explosive "models" of nuclear experiments. As research under the joint Atomic Energy Commission—Corps of Engineers program progressed, exca-

vation with large chemical-explosive charges appeared to have several potential merits in itself, and the emphasis in the experimental program gradually shifted to investigating the use of more economical explosives and methods of emplacement.

Project Trinidad was a relatively complete program of experimental tests, the objectives of which were to investigate both the fundamentals of cratering and the economic aspects of explosive excavation. The series culminated in the successful completion of an actual railroad cut for the relocation of the Colorado and Wyoming Railroad.

The site was selected because of two factors. The cratering characteristics of the interbedded sandstones and shales were unknown and would represent a valuable contribution to cratering technology. Also, it is the policy of EERL to carry out its research activities at the locations of approved Corps of Engineers Civil Works projects whenever possible. An earthfill dam on the Purgatoire River is scheduled for construction near the town of Trinidad, and it was believed that some of the information acquired in the cratering experiments might find application to associated projects. This was indeed the case; two additional railway cuts were excavated during the preparation of this report.

This report covers only the initial experimental work performed at Trinidad, including the first railway cut. A considerable amount of additional cratering experimentation was performed during late 1970 and through 1971. Included in these later experiments were Project Middle Course I,¹ Project Minimound,² and Project Middle Course II.³ The last two railway cuts, designated RR2 and RR3, are also the topic of a separate report.⁴

SCOPE OF PROGRAM

It will be helpful to the reader to briefly outline the scope of the cratering

experiments and associated technical programs covered by this report.

Table 1 shows a summary and sequence of the cratering detonations of this project. The A-series consisted of attempts to create emplacement cavities for explosives by means of hole springing. The initial results did not warrant employment of this technique for any of the cratering shots, and the results of this series have been documented in a separate report.⁵

The B-series consisted of eight single 1-ton cratering blasts, three using ANFO (ammonium nitrate and fuel oil) and five using an aluminized slurry blasting agent.

Table 1. Summary of Project Trinidad cratering experiments.

Series	Number	Craters, charges, and explosive	Date
A ^a	—	—	—
B	B1-B3	Three 1-ton single-charge craters using ANFO	} July and August 1970
	B4-B8	Five 1-ton single-charge craters using aluminized slurry.	
C	C1-C3	Three row-charge craters using five to seven 1-ton charges of aluminized slurry; simultaneous detonation.	} September and October 1970
	C4-C5	Two row-charge craters using five 1-ton charges of aluminized slurry; delayed detonation.	
	C6	Two parallel row-charges of five 1-ton charges of aluminized slurry each; both detonated simultaneously.	
D	D1	Row-charge crater through a ridge; nine charges of 200 to 2000 lb ANFO.	} November 1970
	D2	Row-charge crater along sidehill; five 1-ton charges of slurry.	
	D3	Double row-charge crater along sidehill; six 1-ton and six 2-ton charges of aluminized slurry.	
	D4	Double row-charge railway cut; twenty 1-ton and twelve 2-ton charges of aluminized slurry, time delay between rows.	} December 1970

^aHole springing experiments performed intermittently throughout project; topic of separate report.⁵

These single-charge cratering tests were intended to determine optimum burial depths; i.e., to "calibrate" the rock with regard to its cratering characteristics, so that subsequent row-charge detonations could be designed. Further, the B-series was to provide a comparison of the cratering effectiveness of the ANFO with the slurry, and to provide single-charge airblast and seismic data with which the corresponding effects of row-charges could be compared.

The six detonations in the C-series consisted of a variety of row-charges. Three rows were a test of row-charge design procedures, two rows tested the consequences of introducing millisecond delays between charges in a row, and the

last was the simultaneous detonation of two parallel row-charges. Much of the cratering information gathered during these tests was of value in designing the next series of experiments.

There were four detonations in the final phase of the program—the D-series. These experiments had a more practical aspect to them than the preceding tests. The D-series investigated the feasibility of explosively excavating cuts through varying terrain and long side-slopes. The final experiment, D4, was the excavation of a railroad cut 400 ft in length with a delayed, double row of charges.

Seismic measurements (ground motion), airblast observations, and technical photography were an integral part of the

Fig. 1. Organization of Project Trinidad.

program. The results of the major technical programs are discussed in separate chapters.

The seismic and airblast studies were oriented primarily towards comparisons of effects from the large variety of detonations, rather than towards site calibration and legal documentation, although this facet of the program was also important. Because the Government had acquired virtually all of the surrounding structures and because they were unoccupied, it was actually hoped that some damage would be caused, and therefore several of the close-in structures were

monitored for potential damage resulting from the larger detonations.

PROJECT ORGANIZATION

The participating agencies and their functional relationship to the project are shown in Fig. 1. In EERL experiments, operational support is provided by the Army Engineer District having jurisdiction in the geographical area in which experiments are conducted. Drilling and explosives services are acquired by competitive bid.

Chapter 2. Site Description

LOCATION AND TOPOGRAPHY

Project Trinidad was located on the highly dissected uplands of the western Great Plains, about 6 mi west of Trinidad, Colorado (Fig. 2). The region is flanked on the west by the majestic Sangre de Cristo Mountains, on the north by the twin spires of the Spanish Peaks, and on the east by the Great Plains. The Purgatoire River and its tributaries have broken the area into a series of flat-topped mesas bounded by steep-walled, narrow valleys. The test areas were located on the flat benches and gentle sidehills that border the Purgatoire River.

The entire Trinidad site area was located within the boundary of the Trinidad Lake Project, a Corps of Engineers Civil Works program under the Albuquerque District of the Corps of Engineers. The proposed dam will help to develop

the Trinidad area as a recreational and agricultural center for southern Colorado.

Fig. 2. Project Trinidad site location.

The regional climate is semiarid, with most of the precipitation occurring in the summer as thundershowers. Winters are relatively mild with intermittent heavy snowfalls. Average precipitation is 14 in. while the average temperature is about 51°F. The semiarid climate has given rise to a distinctive flora. The dominant trees are juniper, piñon, and scrub oak. Grasses are abundant throughout the area, and several species of cactus thrive.

The test area lies at the center of the once-bustling Trinidad coal field. Coal mining was the life-blood of the area until disastrous strikes and fires gradually closed down the mines. A significant decrease in population has accompanied the decline in coal production. Ruins of once-prosperous mining towns attest to this decline, and the raising of livestock has replaced coal mining as the most important industry in the area. Only the Allen mine, located in the upper valley of the Purgatoire 30 mi west of Trinidad, is still active. Trinidad, with about 9,000 inhabitants, is the major population center of the region.

GEOLOGY

The uplands of the Trinidad area consist of sedimentary rocks of Late Cretaceous to Early Tertiary age. The surface rocks are relatively undeformed and dip gently westward forming the Raton basin. The exposed rocks consist of about 5,000 ft of sediments, three units of which are relevant to the project: the Trinidad sandstone, the Vermejo formation, and the Raton formation. These rocks form the predominant outcrops in the test area. Figure 3 is a generalized

Fig. 3. Generalized stratigraphic section of the Trinidad, Vermejo, and Raton formations.

stratigraphic column of the rocks exposed in the Trinidad area.

The principal structural feature of the Trinidad area is the Raton basin, which is a broad, asymmetrical trough trending

northward. Isolated normal faults are scattered throughout the area. In the test area the beds dip 5 to 8 deg to the northwest.

The cratering experiments of Project Trinidad were carried out in the Vermejo formation of Late Cretaceous age. The Vermejo formation consists of complexly interbedded grey to black, carbonaceous, coaly, and silty shale; buff, grey, and grey-green arkosic sandstone; grey and dark-grey siltstone; and coal. The bedding is thin-to-massive. The thinner beds are parallel stratified and parallel laminated, but the thicker beds are lenticular and irregular. The sandstone is composed of very-fine-to-medium-sized grains of quartz, feldspar, mica, and ferromagnesian minerals cemented by clay and calcium carbonate. The sandstone is highly friable and contains carbonized plant remains. The shale is mostly nonfissile and has a wide range of sand and carbonaceous content. The coal beds, which are interbedded with the shale and siltstone, are of bituminous grade and have been extensively mined. Stratigraphic columns taken from the core holes in the test area are shown in Appendix A.*

Overburden in the test area consists of very clayey soil. Platy fragments of sandstone and rounded river-run cobbles are common in the soil. Overburden thicknesses vary from 0 to 15 ft in the test area.

PRESHOT ENGINEERING PROPERTIES OF SITE MEDIUM

This section presents a summary of the engineering properties of the rock at

the Project Trinidad site. The results of the laboratory physical tests are presented in Appendix A.*

The unconfined compressive strength of the intact rock ranges from about 450 psi for shale and coal to 8,000 psi for sandstone. The wide range in compressive strengths reflects the different rock types and the presence of fractures in some of the samples.

Water content of the rocks at Trinidad ranges from 1.2 to 9.2%. The degree of saturation ranges from 58.3 to 99.6, with an average of about 78%. Porosity values range from 5.3 to 17.0%, and averages about 10%.

The material at the Trinidad test site has an average in situ density of 156 lb/ft³ (2.5 g/cm³).

Seismic velocities at the Trinidad site varied greatly. Overburden and weathered rock velocities ranged from 1,000 to 2,500 feet per second (fps), a representative velocity for overburden and weathered rock was 1,250 fps. Interbedded sandstone and shale and thinly bedded sandstone had velocities ranging from 2,500 to 6,000 fps (a representative velocity is 5,000 fps). The massive, unweathered sandstone had a velocity that ranged from 7,000 to 8,500 fps (a representative velocity is 7,500 fps).

The rock quality designation, RQD,⁶ was used to determine a qualitative index of the in situ rock mass. The quality of the rock as determined by this method was fair-to-poor (RQD's ranged from 39 to 56%). The RQD was developed by Deere and is used as a measure of the in situ quality of the rock. Specifically,

* Figures A3 through A6.

* Tables A1 through A3.

the RQD is the percentage of core recovery computed by considering only pieces of core longer than 4 in. as recovered. Smaller pieces are considered to be due to close shearing, jointing, faulting, or weathering in the rock mass and are not counted. Core loss, weathered and soft zones, are accounted for in the determination. RQD values ranging from 0 to 50% are indicative of a poor quality rock mass having a small fraction of the strength and stiffness measured for an intact specimen.

The laboratory tests provided another classification based on unconfined compressive strength and modulus of elasticity.⁷ The test results are plotted in Fig. 4 and indicate the rock to be of weak-to-intermediate strength.

Fig. 4. Engineering classification for intact rock (after Deere and Miller⁷).

Chapter 3. Crater Measurements

This chapter presents the cratering information acquired during the B, C and D series of detonations, each series being described in sequence. Some comparative information on explosives, based on the crater measurements, is also included in the discussion. All crater measurements were obtained from plots of conventional survey data, and the volumes of single craters are based on their cross sections and the CRATER DATA computer code.⁸ Volumes of row craters are based on cross sectional areas measured with a planimeter and the application of Simpson's rule.

Preshot and postshot ground surveys were made along two orthongonal lines for the single craters, and at selected locations along the alinements of the row craters.

A postshot aerial view of the primary test area, showing most of the craters in Project Trinidad, is shown in Fig. 5. Experiments D1, D2, and D3 were located in another area about a mile away. The craters in the blocked-off areas in Fig. 5 were part of separate studies^{1, 5} and are not discussed in this report. A preshot topographic map of the same area is shown in Appendix A.

Fig. 5. Aerial view of principal experimental area showing B series, C series, and the D4 crater.

B-SERIES

The B-series consisted of eight 1-ton charges detonated at various depths of burst. The principal objectives of this

series were to obtain optimum crater dimensions and depths of burst to be used as a design base for the follow-on row-charge experiments, and to compare the cratering effectiveness of ANFO and a

metallized slurry. The design approach was to assume that the optimum depth of burial would be near $1.9 \text{ ft}/E^{1/3}$ (where E is the total energy of the explosive in Mcal), and then to bracket this depth. The value of $1.9 \text{ ft}/\text{Mcal}^{1/3}$ was based on previous cratering experience. In this manner cratering curves could be developed to determine the optimum depth of burial. ANFO was used as the explosive in Detonations B1 through B3, and an aluminized ammonium-nitrate slurry was used in Detonations B4 through B8. Table 2 summarizes the charge emplacement conditions.

The explosives were emplaced in 3-ft diameter holes drilled with the bucket auger shown in Fig. 6. A considerable amount of auxiliary drilling and blasting was required to break the rock in most of the emplacement holes so that it could be removed with the bucket auger. An air-

operated, track-mounted drill was used for this supplementary drilling.

After the explosives were emplaced, the holes were stemmed with a mixture of drill cuttings, 3/4-in. aggregate, and water. Except for the two delayed row-charges, primacord initiated by an electric cap at the surface was used to detonate the charges. A column of boosters extending the full height of the cratering charge was used in all cases. The characteristics of the explosives used in the various phases of the project are shown in Table 3.

The results of the crater measurements program for the 1-ton B-series are given in Table 4. One of the B-series craters is shown in Fig. 7. The apparent radii and the depths of the craters are plotted against depth of burial in Fig. 8, and the apparent crater volumes are plotted against depth of burial in Fig. 9.

Table 2. B-series cratering charges.

Detonation	Explosive	Hole Depth (ft)	Depth to top of charge (ft)	Charge height (ft)	Depth of burst		Detonation	
					Actual (ft)	Design (ft)	Date	Time
B1	ANFO ^a	18.1	12.4	5.7	15.2	16.0	13 Aug 71	0900
B2	ANFO	20.7	15.4	5.3	18.0	18.0	14 Aug 71	1100
B3	ANFO	22.3	17.1	5.2	19.7	20.0	12 Aug 71	0810
B4	AANS ^b (TD-2)	17.9	13.9	4.0	15.9	16	13 Aug 71	1400
B5	AANS (TD-2)	20.4	16.8	3.6	18.6	19	11 Aug 71	1400
B6	AANS (TD-2)	22.8	19.0	3.8	20.9	21.5	10 Aug 71	1115
B7	AANS (TD-2)	24.3	20.9	3.4	22.6	24.0	12 Aug 71	1440
B8	AANS (TD-2)	30.0	26.3	3.7	28.1	28.0	11 Aug 71	0835

^aANFO" is the commonly used abbreviation for the explosive consisting of ammonium nitrate (94.5%) and fuel oil (5.5%).

^bAANS designates an aluminized ammonium nitrate slurry. This slurry explosive consists primarily of ammonium-nitrate and contains powdered aluminum for greater energy; the explosive was designated TD-2 by the manufacturer, IRECO Chemicals.

Fig. 6. Bucket auger used to emplace charges.

Fig. 7. Typical 1-ton single-charge crater.

Cross sections of the apparent craters are contained in Appendix B.

Considering the wide lateral variations in near surface geology that exist at the test area, the data points in Figs. 8 and 9 show remarkably little scatter about the (visual) best-fit curves drawn through the points. The anomalous appearing cross-over of the crater radius curves for slurry and ANFO can probably be attributed to almost 10 ft of overburden present

Fig. 8. Apparent crater radii and depths for B series.

Fig. 9. Volumes of B series apparent craters.

at the location of Detonation B3. Overburden depths at the other ground zeros did not exceed 4 ft, except for B4 which has 9 ft.

On the basis of Figs. 8 and 9, the following optimum crater dimensions for

Table 3. Characteristics of Project Trinidad explosives.

Detonation	Explosive	Density (g/cm ³)	Detonation ^a velocity (m/sec)	Bubble ^{a,b} energy (cal/g)	Aluminum ^a content (%)
B1-B3 D1	ANFO ^c	0.9	4000	450	—
B4-B8 C1-C6 D4	AANS ^d (TD-2) ^e	1.35	4450	860	18
D2	AANS (TD-1) ^e	1.25	4500	540	5
D3	AANS (IR-10) ^f	1.25	5450 ^{f,g}	1130 ^{f,g}	25

^aAll information supplied by manufacturers prior to experiments.

^bThe bubble energy of an explosive is considered a useful indication of the overall explosive energy; it is more readily measured than shock energy.

^cAmmonium nitrate and fuel oil.

^dAluminized ammonium nitrate slurry.

^eManufacturer's designation; formulated for Project Trinidad by IRECO Chemicals (slurry).

^fManufacturer's designation; manufactured by Gulf Chemicals (slurry).

^gAfter the completion of the experiments, the bubble energy of IR-10 was reported by the manufacturer to be approximately 400 cal/g, and the detonation velocity 4040 m/sec.

1-ton charges were selected for use in future designs:

	Explosive	
	ANFO	TD-2
Radius (ft)	20	23
Depth (ft)	11	13
Depth of burial (ft)	17	18
Volume (ft ³)	6000	9000

A comparison of the relative cratering efficiencies of the two explosives, ANFO and the TD-2 slurry, can be made on the basis of the optimum crater dimensions and volumes. Let us assume that 1 ton of the TD-2 explosive is a more effective cratering explosive than an equal weight of ANFO by a factor "k"; i.e., 1 ton of TD-2 will produce the same crater as k tons of ANFO. We also assume that dimensions scale as the charge weight to the 0.3 power. The actual dimensions of the

largest B-series crater formed by 1 ton of each explosive are:

	TD-2	ANFO
Radius (ft)	23.3	20.0
Depth (ft)	13.0	11.5

So that comparing radii:

$$\frac{\text{radius TD-2}}{\text{radius ANFO}} = k^{0.3} = \frac{23.2}{20.0} = 1.16;$$

therefore,

$$k = 1.64.$$

And comparing crater depths:

$$\frac{\text{depth TD-2}}{\text{depth ANFO}} = k^{0.3} = \frac{13.0}{11.5} = 1.13;$$

therefore,

$$k = 1.5.$$

Table 4. B-series crater dimensions.^a

Detonation	Depth of burst, DOB (ft)	Apparent crater radius, R _a (ft)	Apparent crater depth, D _a (ft)	Lip crest radius, R _{al} (ft)	Lip height, H _{al} (ft)	Lip radius, R _{eb} (ft)
B1	15.2	17	8.0	22	2.5	60
B2	18.0	20	11.5	25	3.8	60
B3	19.7	24	6.5	27	1	35
B4	15.9	23.5	12.8	28	3.1	60
B5	18.6	23.2	13.0	30	3.4	70
B6	20.9	21.5	11.5	29	3.7	70
B7	22.6	20.2	6.0	32	2.6	60
B8	28.1	— ^b	— ^b	— ^b	— ^b	— ^b

^aCross-sections of the apparent craters are presented in Appendix B; a diagram showing standard crater nomenclature appears as Fig. B1.

^bMound; charge buried too deep to crater.

And comparing crater volumes:

$$\frac{\text{volume TD-2}}{\text{volume ANFO}} = k = \frac{9000}{6000} = 1.5.$$

The values of k resulting from the comparisons above indicate that the aluminized TD-2 slurry is about 50% more effective as a cratering explosive than ANFO. The TD-2 explosive was used for the entire C-series (which immediately followed the single-charge experiments described above) and for the D4 railway cut. ANFO was used, however, in the next two railway cuts, RR-2 and RR-3.⁴

C-SERIES

There were six row-charge detonations in this series: three rows in which the charges were detonated simultaneously, two in which millisecond delays were introduced between charges, and one simultaneously detonated double row.

The three simultaneously detonated rows were designed to test a hypothesis

of row crater "enhancement." The term enhancement designates the increase in width and depth of a row crater that occurs when the spacing between charges in a row is progressively reduced. The degree of enhancement is simply the ratio of the depth or width of a row crater to the depth or diameter of the single crater that would be created by one of the charges in the row buried at optimum depth. Previous cratering experiments⁹ in a very weak clay-shale resulted in an empirical formulation of a relationship between enhancement and charge spacing.¹⁰ The first three rows, C1 through C3, were to determine whether the same relationship was also valid for relatively stronger rock such as sandstone.

The purpose of the two row-charges with the delays between charges, Experiments C4 and C5, was to observe the reduction of airblast, ground shock, and crater size that would result from the delays. It was believed that the lessening

of crater dimensions might be more than offset by a favorable reduction of the potentially damaging effects of blast and shock, consequently widening the potential for the application of explosive excavation.

In the course of conducting the C-series, the decision was made to excavate explosively a railway cut for the relocation of the Colorado and Wyoming Railroad. The selected excavation was sufficiently wide that a double row of charges would be required. The last experiment in the C-series, C6, was an attempt to acquire design information about double row-charges.

The explosives were emplaced in the same manner as in the B-series; i.e., in 3-ft diameter holes drilled with a bucket auger. Each charge was nominally 1-ton of the IRECO TD-2 ammonium-nitrate slurry. Holes were stemmed with pit-run gravel, a small amount of drill cuttings, and water. The simultaneous rows were detonated with primacord, and the two delayed rows used a specially fabricated delay-cap assembly, which was embedded in sand a foot or two above the charges. Charge emplacement data are summarized in Table 5.

Simultaneous Rows (C1, C2, C3)

Rows C1, C2, and C3 were designed according to the following relationship between enhancement and charge spacing:

$$e^2 = \frac{1.4}{S/R_a}$$

where

e = enhancement of row crater dimensions relative to dimensions of optimum single crater

S = charge spacing

R_a = optimum single crater radius

Row-charges at a given spacing should be buried more deeply than the optimum single-charge depth of burial by the amount of enhancement. The above relationship implies that there will be no enhancement at a charge spacing of $1.4 R_a$.

As previously mentioned, this formula was developed and tested in a series of row cratering experiments⁹ in clay shale. Implicit in the derivation of this relationship is the assumption that a charge in a row is about 30% more efficient in cratering than is a single charge; i.e., one charge in a row of charges will eject 30% more rock than it would if detonated by itself. The concept of row crater enhancement means that the size of the crater can be varied by adjusting the spacing and depth of the charges. For example, a row-charge to excavate a channel with a varying depth of cut can be designed by varying the spacing between charges of equal size as the depth of the cut varies.

The design philosophy for the first three rows (C1, C2, C3) was to emplace each row at a constant but different charge spacing, and then to compare the ratio of observed row crater dimensions to those of a single crater. If the results were in accord with the enhancement equation above, then the principles of row-charge design would be firmly established.

The charge spacings selected for the three rows were $1.4 R_a$, $1.1 R_a$, and $0.8 R_a$, where R_a is the radius of the optimum single crater. These spacings were arbitrarily selected to provide a

Table 5. C-series charge emplacement.

Charge number	Charge spacing (ft)	Hole depth (ft)	Depth to top of charge (ft)	Charge height (ft)	Depth of burst		Detonation	
					Actual (ft)	Design (ft)	Date	Time
C1A	1.4R _a 32.0	19.9	16.5	3.4	18.2	18.0	28 Sep 71	1000
C1B		20.1	16.2	3.9	18.2			
C1C		20.2	16.2	4.0	18.2			
C1D		20.0	16.3	3.7	18.2			
C1E		19.2	15.4	3.8	17.3			
C2A	1.1R _a 25.0	22.1	18.1	4.0	20.1	20.4	29 Sep 71	1000
C2B		22.0	18.3	3.7	20.2			
C2C		22.2	18.6	3.6	20.4			
C2D		21.9	18.4	3.5	20.2			
C2E		20.7	17.2	3.5	19.0			
C3A	0.8R _a 18.0	24.7	21.6	3.1	23.2	23.5	1 Oct 71	0910
C3B		24.8	20.9	3.9	22.9			
C3C		25.7	21.3	4.4	23.5			
C3D		25.0	20.6	4.4	22.8			
C3E		24.9	20.5	4.4	22.7			
C3F		24.7	20.7	4.0	22.7			
C3G		25.4	21.7	3.7	23.6			
C4A	1.1R _a 25.0	22.4	19.4	3.0	20.9	20.4	1 Oct 71 50-msec de- lay between charges	1500
C4B		22.4	18.8	3.6	20.6			
C4C		22.3	19.2	3.1	20.8			
C4D		21.9	18.8	3.1	20.4			
C4E		22.3	18.9	3.4	20.6			
C5A	1.1R _a 25.0	21.7	18.1	3.6	19.9	20.4	2 Oct 71 25-msec de- lay between charges	1000
C5B		22.0	18.8	3.2	20.4			
C5C		21.6	18.4	3.2	20.0			
C5D		21.9	18.4	3.5	20.2			
C5E		22.5	18.5	4.0	20.5			
C6A	1.1R _a 25.0	22.5	17.8	4.7	20.2	20.4	30 Sep 71	1000
C6B		21.7	18.1	3.6	19.9			
C6C		21.7	17.7	4.0	19.7			
C6D		22.0	17.9	4.1	20.0			
C6E		22.6	17.6	5.0	20.1			
C6A'	1.1R _a 25.0	22.4	17.8	4.6	20.1	20.4		
C6B'		22.5	17.8	4.7	20.2			
C6C'		21.8	17.3	4.5	19.6			
C6D'		21.7	17.3	4.4	19.5			
C6E'		22.6	18.2	4.4	20.4			

sufficiently wide range to produce significant changes in crater size.

The results of the C-series are contained in Table 6. Cross sections and profiles for all the C-series craters appear in Appendix B. Figure 10 is a photograph of Crater C3 that illustrates the size of a typical row crater.

The results of the C1, C2, and C3 detonations are summarized in Fig. 11, which shows the crater dimensions, expressed in terms of single-crater dimensions, superimposed on the enhancement equation. The agreement between the result and the enhancement predicted by the equation is reasonable. Deviations from

Table 6. Summary of row crater dimensions.^a

Row	Number of charges	Charge spacing		Average depth of burst (ft)	Half-width ($W_a/2$)			Depth (D_{ar})			Enhancement (avg) ^b			$\frac{W_{al}}{W_a}$	$\frac{H_{al}}{D_{ar}}$
		S/R_a	S		Min	Avg	Max	Min	Avg	Max	Predicted	$W_a/2$	D_{ar}		
		(ft)	(ft)		(ft)	(ft)	(ft)	(ft)	(ft)	(ft)					
C1	5	1.4	32	18.0	21.7	24.0	26.0	10.5	12.8	15.0	1.0	1.04	0.98	1.42	0.42
C2	5	1.1	25	20.0	22.5	25.5	28.5	13.0	14.1	14.8	1.13	1.11	1.08	1.43	0.39
C3	7	0.8	18	23.0	31.7	33.7	34.7	14.3	18.9	22.0	1.32	1.47	1.45	1.42	0.41
C4	5	1.1	25	20.6	24.0	25.4	26.2	8.5	10.8	12.1	(50-msec delay)			1.35	0.39
C5	5	1.1	25	20.2	20.7	26.5	32.2	8.6	12.8	14.6	(25-msec delay)			1.32	0.31
C6	10	1.1	25	20.0	(See profiles and cross sections)						(double row)			—	—

^aCrater dimensions apply to the linear section of the crater, as defined by the shaded area in Fig. B1 of Appendix B.

^bThe dimensions of the optimum single crater, as derived from the B-series, are $R_a = 23$ ft, $D_a = 13$ ft, and optimum DOB = 18 ft. The median crater slope angle (measured at the preshot ground surface) is 34 deg.

Fig. 10. C3 row crater.

Fig. 11. Row crater enhancement vs charge spacing.

the relationship are believed attributable to normal scatter. It appears that the enhancement concept is valid for all practical purposes, although further experiments may lead to modification or refinements.

The results of the three simultaneous rows are presented in a somewhat different format in Fig. 12, in which the row crater dimensions have been superimposed on the single-charge cratering curves for the same explosive. Ideally the row crater dimensions should plot along the lines passing through the origin and the peaks of the curves. Although the information is essentially the same as that shown in Fig. 11, Fig. 12 illustrates the reason that the depth of burst of the charges must be increased as the charge spacing is decreased and the crater becomes larger.

It is interesting to note that the C3 crater, produced by closely spaced 1-ton charges, is equivalent to what would have been excavated by 3.5-ton charges spaced at $1.4 R_a$. This is apparent when the yield increase required for a dimensional increase of 1.46 times is computed:

$$\frac{W_{eq}^{0.3}}{1} = 1.46$$

Fig. 12. Single-charge cratering curves with row-crater dimensions superimposed.

where W_{eq} is the equivalent yield of the 1-ton charges in the C3 row. It follows that:

$$W_{eq} = 1.46^{3.33} \approx 3.5 \text{ tons.}$$

It is implicit in the derivation of the enhancement formula that, for a given rock type, each charge in a row will always excavate the same volume of material regardless of the charge spacing. The unit volume, or cubic feet of apparent crater per ton of explosive, was determined for each row in the C-series. This unit volume is also compared to the optimum single volume and is tabulated in Table 7. The data in Table 7 for rows C1, C2, and C3 show that row C2 deviated the most from the nominal figure of 1.3 for row-charge efficiency relative to that of a single charge. This, however, is not reflected in the crater dimensions, which agree well with the predicted enhancement.

The average volume of apparent crater for rows C1, C2, and C3 is 11,140 ft³/ton of explosive, and when this is compared

Table 7. Unit volumes for C-series row craters.

Row (charge spacing)	Volume/ton of explosive ^a (ft ³)	Volume per ton/ single crater volume
C1 (1.4 R_a)	11,620	1.28
C2 (1.1 R_a)	9,425	1.04
C3 (0.8 R_a)	12,375	1.36
C4 (1.1 R_a) ^b	8,500	0.93
C5 (1.1 R_a) ^c	9,690	1.06
C6 (double row) ^d	8,920	0.98

^aFor linear portion of crater; all craters excavated with TD-2 explosive.

^b50-msec delay between charges.

^c25-msec delay between charges.

^dTwo rows at 1.1 R_a , spaced 1.4 $W_a/2$.

with the 9,100-ft³ volume of the optimum single crater formed by TD-2, the average row charge/single charge efficiency is 1.25. There is insufficient data to warrant changing the value of 1.3, currently in use, to the lower value of 1.25. The average value of 11,140 ft³/ton for the simultaneous row-charges will be used as a reference in the discussion on the delayed rows that follows.

Delayed Row-Charges (C4, C5)

The evaluation of a particular explosive excavation project may indicate that ground shock or airblast constraints would render the project infeasible if all the charges in a row were detonated simultaneously. Two of the C-series detonations, C4 and C5, were planned to determine whether the use of millisecond time delays between charges would reduce ground shock and airblast effects without significantly reducing the volume of material excavated. The charge spacing in these two rows was established at $1.1 R_a$ so that the results could be compared to row C2, the corresponding simultaneously detonated row. However, because C2 had what appears to be an anomalously low unit volume, the delayed rows will be compared with the average unit volume for all three simultaneously detonated rows.

It was necessary to decide before the row-charges were emplaced the time delays to be used. A-50 msec delay was selected for row C4, with the option of delaying the charges in row C5 by either 25 or 100 msec, the final decision to be based on the appearance of the C4 crater. The reduction of the ground shock generated by the C4 detonation was so signifi-

cant that there was no reason to try a longer delay period in C5. Consequently, the 25-msec delay period was chosen for the C5 row.

The dimensions of Craters C4 and C5 are given in Table 5. When these dimensions are compared with the dimensions of row C2, it appears that a delay between charges has almost no effect on crater width and a significant effect on crater depth. With the depth of C2 as a reference, a 25-msec delay reduced the depth of C5 to 91%, and the 50-msec delay reduced the depth of C4 to 77% of the depth of C2. The craters are shallowest at the end at which the delay sequence started. A more meaningful analysis can be made by comparing the unit volumes of the delayed rows to the average unit volume of all three simultaneous rows. When the average unit volume of 11,140 ft³/ton for rows C1, C2, and C3 is taken, the 25-msec delay reduced the volume of apparent crater per ton of explosives to 87% of the average, and the 50-msec delay to 75% of the average. The corresponding reductions of ground shock and airblast are discussed in later chapters.

Double Row-Charge Detonation (C6)

The C6 detonation was originally planned as a single, delayed row. When it became apparent that a double row of charges would be required to achieve the width of a planned railroad cut, a preliminary double-row experiment was believed necessary. One of the rows in the C6 detonation had already been drilled at a spacing of $1.1 R_a$ when the decision was made to convert it to a double row, and so the second row was drilled for the same charge spacing.

The separation between the two rows was set at 1.5 times the half-width ($1.5 W_a/2$) of a single row. The factor of 1.5 was based on observations made in smaller scale experiments, and was believed to be close to the maximum separation that could be used without creating a ridge along the crater bottom. The half-width of a row with a spacing of $1.1 R_a$ is predicted with the enhancement formula:

$$e^2 = \frac{1.4}{1.1} = 1.27$$

$$e = 1.13$$

$$\begin{aligned} \text{and } W_a/2 &= eR_a \\ &= 1.13 \times 23 \\ &\simeq 25 \text{ ft.} \end{aligned}$$

Therefore, the rows were separated by

$$1.5 W_a/2 \simeq 39 \text{ ft.}$$

A cross section near the middle of C6 is shown in Fig. 13, which shows the preshot terrain, the charge emplacement, and the actual crater outline. Additional sections are contained in Appendix B. Ideally, C6 would be expected to have an average depth of eD_a ($1.13 \times 13 = 14.7$ ft) over the 39 ft wide portion between the rows. From Fig. 13 it is evident that this depth was not achieved and that the crater was shallower. The shallowest portions of the crater are on the down-slope side of the preshot terrain. The average depth of C6 for the area between the rows is 11.5 ft. The shallowest cross section has an average depth of 11.0 ft

and the deepest cross section an average depth of 14.7 ft. As shown in Table 6 the average amount of material excavated by each charge was 98% of the optimum single 1-ton crater volume.

A subsequent review of available information on double row detonations indicated that the use of a short time delay between the detonation of the two rows would produce a larger crater. Several small scale experiments confirmed this, and a time delay was incorporated into later double row experiments at Trinidad.

D-SERIES

Tests of the D-series were intended to provide an opportunity to experiment with row-charges in nonlevel terrain. Almost all of the previous EERL experience with row charges had been with detonations in predominantly level and flat terrain.

There were several objectives for the D-series experiments. The first experiment, D1, was designed according to the concept of enhancement to cut a channel with a constant bottom elevation through a ridge-like topography. Two sidehill cuts were attempted, one with a single row of charges (D2) and one with a double row of charges (D3). The final D-series detonation was a delayed double row to excavate a railroad cut. The pertinent information is summarized in Table 8.

Single-Row Charge through Varying Terrain (D1)

This shot was a single row of ANFO charges designed to cut a channel with a constant bottom elevation through a ridge. For design purposes, the deepest portion of the cut was assumed to be 15 ft and the

Fig. 13. Longitudinal profiles, charge layout, and cross sections of C6 crater.

length was 110 ft. The shot was designed using varying charge weights and constant enhancement; i.e., a constant charge spacing in terms of S/R_a .

Figure 14 is a profile view of the charge layout showing the design depth and the actual crater bottom along both the centerline and the deepest portion of the crater.

The single crater dimensions for ANFO were used to design this experiment. The optimum dimensions, observed in the B-series, were:

$$R_a = 20 \text{ ft/ton}^{0.3}$$

$$D_a = 11 \text{ ft/ton}^{0.3}$$

$$\text{dob} = 17 \text{ ft/ton}^{0.3}$$

Table 8. Summary of D-series experiments.

Row-charge	Number of charges (lb)	Explosive ^a	Weight of explosive (lb)	Description
D1	9 (200 to 2000)	ANFO	9,800	Single row to excavate cut through ridge.
D2	5, 1-ton	TD-1	10,000	Single row along side hill.
D3	5, 2-ton 6, 1-ton	IR-10	32,000	Double row of charges along side hill.
D4	20, 1-ton 12, 2-ton	TD-2	88,000	Double row, delayed; railway cut 400 ft long.

^aDesignations defined in Table 3.

The design was started at the deepest point of the cut, arbitrarily selected to be 15 ft. It was also decided that charge weights would not exceed 2,000 lb. Because an unenhanced 1-ton ANFO charge will excavate a depth of 11 ft, the required amount of enhancement to cut 15 ft with a 1-ton charge is computed:

$$e = \frac{15}{11} = 1.36;$$

so that the charge spacing to achieve this enhancement can be computed as:

$$S/R_a = \frac{1.4}{2} = \frac{1.4}{1.85} = 0.76.$$

This spacing was rounded to $S/R_a = 0.8$.

The method of computing the weights and spacings of the remaining charges in the row are documented in Ref. 11. As an example of this design procedure, refer to Fig. 14 and consider the charge immediately to the right of the 2,000-lb charge at 0+68. The weight and position of this charge was determined by measuring the depth of cut a distance $0.8 R_a$ to the right of the first charge (i.e., $0.8 \times R_a$ for a 2,000-lb ANFO charge = $0.8 \times 20 = 16$ ft). This depth of cut is approx-

imately 12.5 ft. Because we are using enhancement of 1.36, this depth can be reduced by this factor in order to compute the charge weight required at this location. We therefore have an effective depth of cut of:

$$\frac{12.5}{1.36} = 9.2 \text{ ft,}$$

and the charge weight required, W , can then be found:

$$\frac{2000^{0.3}}{11} = \frac{W^{0.3}}{9.2}$$

$$W^{0.3} = 2000^{0.3} \times \frac{9.2}{11}$$

$$W = 1120 \text{ lb.}$$

This weight was rounded to 1,200 lb to be slightly conservative. The charge is then placed at a distance from the 2,000-lb charge equal to the average of 0.8 times the crater radii of the two adjacent charges. The crater radius for a 1,200-lb charge is:

$$20 \left(\frac{1200}{2000} \right)^{0.3} \approx 17 \text{ ft.}$$

The spacing is then $0.8 \left(\frac{20 + 17}{2} \right) \approx 15$ ft.

Fig. 14. D1 crater preshot terrain, charge layout, cross sections, and crater profile.

The same procedure is followed for the remaining charges. As indicated above, this procedure is more fully explained in Ref. 11. Table 9 contains the charge emplacement data for Experiment D1.

The D1 crater had a maximum depth of 19 ft, and the average depth along the deepest part of the crater was 15.2 ft. The cross sections in Fig. 14 show that the deepest part of the crater was offset about 10 ft downhill from the centerline.

Table 9. D1, D2, D3 charge emplacement.

Charge number	Hole depth (ft)	Depth to top of charge (ft)	Charge weight (lb)	Charge height (ft)	Depth of burst		Detonation		Temperature (deg)	Wind (mph)	Weather
					Actual (ft)	Design (ft)	Time (MST)	Date			
D1A	15.2	11.6	300	3.6	13.4	13.0	1115	17 Nov 70	51	5NE	Clear
D1B	18.4	15.9	700	2.5	17.1	17.5					
D1C	22.1	18.4	1200	3.7	20.2	20.5					
D1D	24.5	21.1	1700	3.4	22.8	23.0					
D1E	26.0	20.1	2000	5.9	23.0	23.5					
D1F	26.2	21.2	2000	5.0	23.7	23.5					
D1G	22.0	18.5	1200	3.5	20.2	20.5					
D1H	16.5	14.9	500	1.6	15.7	16.0					
D1I	12.3	10.8	200	1.5	11.5	11.0					
D2A	22.3	13.3	2000	9.0	17.8	18.0	1030	18 Nov 70	49	0	Clear
D2B	22.2	13.5	2000	8.7	17.8						
D2C	22.3	13.0	2000	9.3	17.6						
D2D	22.1	13.5	2000	8.6	17.8						
D2E	22.0	13.1	2000	8.9	17.5						
D3A	22.1	15.8	2000	6.3	19.0	19.0	1015 ^a	19 Nov 70	45	0-5E	Clear
D3B	22.2	16.3	2000	5.9	19.2						
D3C	21.5	16.2	2000	5.3	18.9						
D3D	22.5	16.6	2000	5.9	19.5						
D3E	22.2	16.9	2000	5.3	19.5						
D3F	21.7	15.7	2000	6.0	18.7						
D3A'	28.9	18.3	4000	10.6	23.6	25.0					
D3B'	29.3	19.1	4000	10.2	24.2						
D3C'	29.5	20.5	4000	9.0	25.0						
D3D'	29.7	20.3	4000	9.4	25.0						
D3E'	29.5	18.6	4000	10.9	24.0						
D3F'	30.2	18.6	4000	11.6	24.4						

^aD3' delayed 250 msec after D3.

The maximum depth beneath the center-line of the charges was about 16 ft, and the average half-width at the center of the cut was 34 ft. Figure 15 is a photograph of the D1 crater.

A rather surprising result of the D1 detonation is the volume of apparent crater that was excavated. The volume of the crater from 0+10 to 0+90 is 47,200 ft³. The charge weight distributed over this portion of the crater was about 8,450 lb, so that the unit volume is 11,170 ft³/ton

Fig. 15. D1 crater.

of explosive. This unit volume is nearly a factor of two larger than the observed volume of the optimum single crater excavated by ANFO. The reason for this is not clear. The sidehill topography may have resulted in more material being ejected than would have occurred in level terrain, and the single ANFO crater used as a reference may not have been representative.* It appears that despite its smaller total energy content compared to some of the metallized slurries, ANFO is nevertheless an excellent cratering explosive, especially when cost is considered.

Single Row-Charge along a Sidehill (D2)

The charges for the D2 experiment were emplaced in a row along a sidehill. The D2 experiment did not have a specific design objective. Rather, it was a case of emplacing the charges in a row along a sidehill to observe the influence of the slope on crater size and shape.

The experiment was originally designed with the assumption that the TD-2 explosive would be used. However, after the emplacement holes had been drilled at a spacing of $1.4 R_a$ for TD-2, it was decided to use the less energetic explosive TD-1 because of a surplus. The bubble energy of TD-1 is 540 cal/g compared to 860 cal/g for the TD-2. When it is assumed that crater dimensions vary as the 0.3 power of the bubble energy,[†] TD-1 should produce a smaller

crater than one produced with TD-2, and it should be smaller by a factor of:

$$\left(\frac{540}{860}\right)^{0.3} = 0.87.$$

If this factor is valid, then the charge spacing for the TD-1 explosive in the D1 experiment was actually $1.4/0.87 = 1.6 R_a$.

Figure 16 shows the centerline profile and charge emplacement, the deepest profile of the crater, and selected cross sections.

The charges were buried at a nominal depth of 18 ft, which is a few feet deeper than optimum for this explosive. With the same factor 0.87 that was used to obtain a crater radius for TD-1, the optimum depth of burial for 1-ton of TD-1 would be 18×0.87 , or approximately 15.5 ft. Burial depths in this sloping terrain are referred to the nearest free surface rather than the vertical distance between charge and ground surface; in gently sloping terrain there is very little difference.

All charges were detonated simultaneously and the appearance of the crater is shown in Fig. 17. The profiles in Fig. 16 show some cusping between charges caused by the wide spacing. The cusps were about 2 ft higher than the low points in the crater bottom. The average crater depth at its deepest was 7.3 ft (vertical). The unit volume for the D2 crater was $8,000 \text{ ft}^3/\text{ton}$. Although this figure appears to be low compared to the average value of $11,140 \text{ ft}^3/\text{ton}$ realized in rows C1, C2, and C3, it is in reasonable agreement with what would be expected on the basis of relative explosive energies. When it is assumed that crater volumes are roughly proportional to bubble energies, D2 could

*A later experiment in the same area, Railroad Cut RR3 detonated in September 1971 had a unit volume nearly identical to D1; it was also on a sidehill-ridge topography.⁴

†The total energies of the explosives will be very nearly proportional to their bubble energies.

Fig. 16. Longitudinal profiles and cross section of D2 crater.

be expected to have a unit volume close to:

$$\frac{540}{860} \times 11,140 = 7,000 \text{ ft}^3/\text{ton}.$$

That this nominal unit volume was exceeded could be attributed to less fallback into the crater because of the sloping terrain. The deepest portion of the crater

Fig. 17. D2 crater.

is offset about 20 ft downslope from the centerline of the charges, and slumping of the upslope crater wall appears to have occurred.

Although the apparent crater would be only marginal as a potentially useful excavation, there is a large amount of broken rock in the form of fallback that could be excavated and shaped into a useful cut with conventional machinery. The total volume of broken rock probably exceeds the volume of the apparent crater by at least a factor of three. In some applications of explosive excavation in which machinery would be used to excavate the rock, large charges would be buried deeper than cratering depths to break and "mound" the rock; i.e., no ejection from the crater would occur. This technique has been successfully applied in subsequent experiments.^{2,12}

Double Row-Charge along a Sidehill (D3)

The primary purpose of the D3 experiment was to test the feasibility of excavating a relatively wide cut along a sidehill by means of two parallel row charges.

Profiles and cross sections of the D3 crater, both preshot and postshot, are shown in Fig. 18. There were six charges in each row, the downslope row consisting of 1-ton charges and the upslope row containing 2-ton charges. The explosive, which was surplus from another project, was manufactured by Gulf Chemicals and was designated IR-10. It was an ammonium-nitrate base slurry with a reported aluminum content of approximately 25%. The charges were emplaced in 3-ft diameter holes.

The IR-10 slurry was reported to have a bubble energy of 1,130 cal/g. On the basis of this value of bubble energy relative to that for TD-2, the following optimum single-crater dimensions were estimated for designing D3:

	R_a (ft)	D_a (ft)	DOB (ft)
TD-2 (1 ton)	23	13	18
IR-10 (1 ton)	25	14	19.5
IR-10 (2 tons)	31	16	24

The 1-ton charges in the downslope row were spaced at $1.4 R_a$ apart, which is 35 ft. The 2-ton charges in the upslope row were also spaced 35 ft apart, which is equivalent to $1.13 R_a$ (i.e., $35/31$). A single row of charges at this spacing in level terrain should produce an enhancement of single crater dimensions of 1.12; consequently, the optimum depth of burst would be 27 ft (i.e., 1.12×24). The 2-ton charges were placed so that they were approximately 27 ft from the assumed true crater boundary produced by the downslope row. The charges were buried so that they were also about 27 ft deep. The detonation of the row of 2-ton

Fig. 18. Longitudinal profiles and cross sections of D3 crater.

charges was delayed 250 msec after the detonation of the downslope row.

The D3 experiment also included an attempt to shape the uphill wall of the crater by means of a presplit plane. The 20-ft deep presplit holes were 2.5 in. in diameter, spaced 2 ft apart, and loaded with 0.25 lb of dynamite per foot. The presplit holes were fired before the main charges and were located along the assumed true crater boundary.

Figure 19 is a photograph of the D3 crater. The crater is broad and shallow, resembling the D2 crater in appearance.

Fig. 19. D3 crater.

The mound in the middle of the crater may have been the result of only partial detonation of a charge. That this occurred is simply a matter of speculation; however, the side-on high-speed film of the experiment did show a pronounced low point in the rising mound at this location.

The apparent crater volume per ton of explosive, averaged over the linear portion of the crater, is $9,040 \text{ ft}^3/\text{ton}$. This unit volume was unexpectedly low in comparison to the average of $11,140 \text{ ft}^3/\text{ton}$ realized in the C-series, especially in view of the reported high bubble energy of the explosive. As previously mentioned, the IR-10 explosive was surplus from another project, and it may have deteriorated during the 6 mo it was in storage although there is no test information to substantiate this hypothesis. Further, there is a major discrepancy in the values of bubble energy reported by the manufacturer. The original value of $1,130 \text{ cal/g}$ is in Table 3, and it is this value that was used in the design of D3. After the experiment, a much lower value of bubble energy, approximately 400 cal/g , was reported for this explosive. If the lower value is the correct one, then the charges were buried too deeply and spaced too far apart. It is interesting to note that, comparing the volume of the D3 crater to the average of $11,140 \text{ ft}^3/\text{ton}$ excavated by TD-2, the IR-10 would have a bubble energy of roughly 680 cal/g .

It is possible that the delay time between the two rows was too long and that the interaction of ejecta from the two rows was detrimental to cratering efficiency. The high-speed film of the detonation, taken by a camera aimed along the alinement of the rows, suggested that

the delay time probably was too long. The mound from the downhill row may have been too well developed at the time the second row of charges was detonated. The decision was made to use a shorter delay time between the rows of the follow-on D4 experiment.

The depth of the D3 crater, averaged over the entire linear portion of the crater, was 10.7 ft. The maximum depth was 15.5 ft and the shallowest portion was 5.5 ft deep. If the mound in the crater bottom is disregarded, then the average depth is about 12.5 ft.

The presplitting did not result in a smooth, planar face on the upslope wall of the crater, although portions of the presplit holes were visible near the surface. It is believed that the low strength of the rock and slumping prevented the formation of a clean wall. It appears that the presplit plane was located at the correct distance from the main charges because there was little or no disturbance of the ground surface beyond their location. It is possible that removal of the fallback would have revealed the existence of a presplit surface at depth, say 15 ft, but this was not done. There is still no reason to believe that presplitting cannot be used in conjunction with cratering detonations, but more experimentation is definitely needed.

Delayed Double Row-Charge (Railway Cut, D4)

The D4 experiment* was designed to excavate a 400-ft cut along the realignment of the Colorado and Wyoming

*Because of additional railway cuts excavated later, the D4 experiment is also referred to as RR1; i.e., the first railroad cut.

Railroad. The terrain in the area of the cut was varying, with a portion of the cut along a gentle sidehill. Design depth of the cut ranged from 15 to 20 ft and the required width at subgrade elevation was 46 ft. Conventional excavation of the cut would have required the removal of approximately 13,000 yd³ of earth and rock. The location of the cut is shown in Fig. 5.

The explosive array consisted of two parallel rows of charges. The anticipated cross section and a plan view of the charge array are shown in Fig. 20. The

Fig. 20. Anticipated cross section and plan view of D4 experiment.

north row consisted of eighteen 1-ton charges and the south row consisted of twelve 2-ton and two 1-ton charges, a total of 32 separate charges and 44 tons of explosive. The rows were alined parallel to the railway centerline but were offset 23 ft on both sides of the centerline. Each row was designed separately according to the terrain elevation along its alinement. A constant-yield (i. e., varying-enhancement) design was used for both rows.

In the varying enhancement design method, the spacing (S/R_a) of the charges in a row is varied rather than their weight in order to accommodate varying depths of cut. The depth of cut is equated to the enhanced crater depth; i. e.:

$$\text{depth of cut} = eD_a = \left(\frac{1.4}{S/R_a} \right)^{1/2} D_a,$$

where D_a is the depth of the single crater formed by the selected charge weight. A

Fig. 21. Chart of charge spacing vs depth of cut for 1- and 2-ton charges of TD-2 slurry in sandstone and shale.

simple chart can be prepared showing the required charge spacing for a given charge weight and depth of cut. The chart used for designing the D4 cut is shown in Fig. 21. Two-ton charges were used wherever the depth of cut was greater than 16 ft to minimize the number of drill holes required. As mentioned before in the discussion of the C-series, the charges must be buried deeper as they are spaced closer together.

The separation between the rows was fixed at 46 ft along the entire length of the cut. As a consequence of the fixed separation between rows, the row separation expressed in terms of the row-crater width varied with the depth of the cut. At the deepest portion of the cut the row separation was 1.45 times the average* half-width of a single row crater [i.e., $1.45 W_a/2$ (average)], and at the shallowest portion the separation was $1.70 W_a/2$ (average). The charge spacing within each row varied from $0.90 R_a$ to $1.25 R_a$.

Table 10 contains a summary of the charge emplacement data for D4. Two methods were employed for drilling the emplacement holes for the explosive. The northern line of 1-ton holes was drilled using an "underreamer." The procedure consisted of drilling an 18-in. pilot hole and expanding the bottom portion of the hole to 36 in. with expanding arms on the drill bit. The southern line of 2-ton holes was drilled to depth with a bucket auger at the full charge-cavity diameter of 30 in. The holes were loaded by pumping the slurry directly into the

emplacement hole from the mixing truck. A delay of approximately 150 msec was introduced between the detonation of the two rows, with the northern (1-ton) row being fired first.

The development of the mound and ejecta is shown several seconds after detonation in Fig. 22, and Fig. 23 shows

Fig. 22. D4 detonation.

Fig. 23. D4 crater viewed from west to east along center line of railroad.

*By "average" is meant the mean half-width of the row craters formed by the row of 1-ton charges and the row of 2-ton charges.

Table 10. D4 charge emplacement summary.

Charge number	Station	Hole depth (ft)	Depth to top of charge (ft)	Charge weight (tons)	Charge height (ft)	DOB (ft)
A. South Line						
D4A'	91+00	21.3	18.0	1	3.3	19.7
D4B'	91+27	26.2	19.8	2	6.4	22.0
D4C'	91+55	29.6	20.5	2	9.1	25.0
D4D'	91+80	30.3	20.2	2	10.1	25.2
D4E'	92+05	30.3	20.2	2	10.1	25.2
D4F'	92+31	28.3	19.2	2	9.1	23.7
D4G'	92+60	27.2	18.3	2	8.9	22.8
D4H'	92+93	26.3	20.1	2	6.2	23.2
D4I'	93+28	26.4	17.4	2	9.0	21.9
D4J'	93+63	25.9	14.5	2	11.1	20.0
D4K'	93+96	27.2	16.7	2	10.5	21.9
D4L'	94+29	26.5	16.4	2	10.1	21.4
D4M'	94+65	24.2	12.8	2	11.4	18.5
D4N'	95+00	19.8	14.0	1	5.8	16.9
B. North Line						
D4A	91+00	20.7	13.9	1	6.8	17.3
D4B	91+26	19.0	15.5	1	3.5	17.2
D4C	91+54	22.2	18.6	1	3.6	20.4
D4D	91+78	22.6	18.7	1	3.9	20.6
D4E	92+00	23.1	18.3	1	4.8	20.7
D4F	92+22	23.4	17.4	1	6.0	20.4
D4G	92+47	21.0	15.4	1	5.6	18.2
D4H	92+74	20.3	15.5	1	4.8	17.9
D4I	93+03	20.6	15.9	1	4.7	18.2
D4J	93+32	20.1	16.4	1	3.7	18.2
D4K	93+59	20.3	16.3	1	4.0	18.3
D4L	93+83	23.3	18.8	1	4.5	21.0
D4M	94+03	24.2	20.6	1	3.6	22.4
D4N	94+22	23.3	21.0	1	2.3	22.1
D4O	93+41	23.9	19.4	1	4.5	21.6
D4P	94+60	23.6	19.0	1	4.6	21.3
D4Q	94+79	23.8	18.0	1	5.8	20.9
D4R	95+00	22.9	18.0	1	4.9	20.4

Fig. 24. Cross sections of D4 railway cut showing comparison between crater and cut excavated by conventional methods.

the resulting crater. Four cross sections through the crater are shown in Fig. 24.

A total volume of 18,000 yd³ of material was ejected by the blast, which is

equivalent to a unit volume of 11,000 ft³/ton of explosive. This value is nearly the same as the average for the three simultaneous C-series row craters, and indicates that the delayed double row was

very efficient, particularly when compared to the unit volume of only 8,900 ft³/ton excavated by the simultaneously detonated double row, C6.

Chapter 6 contains a description of the postshot work required to transform the D4 crater into a useful railway cut.

Chapter 4. Seismic Measurements

This chapter presents a summary of the seismic ground motion program. The objectives were to collect and to compare data on the seismic signals generated by the wide variety of cratering detonations in the project. Only a brief analysis of peak motions is presented in this chapter; Ref. 13 contains a more detailed treatment of the data.

SCOPE

The bulk of the information was recorded by personnel of the Soils Division of the USAE Waterways Experiment Station (WES). Conjunctive studies of the structural response of the intake tower and surveys of several close-in residential buildings were performed by the firm of

Fig. 25. Locations of seismic monitoring stations during Project Trinidad.

John A. Blume and Associates of San Francisco. A supplemental program of monitoring building response was carried out by the Special Projects Party of the National Ocean Survey (Las Vegas) during the D1, D2, and D3 detonations.¹² This work was performed at the request of the Nevada Operations Office of the AEC.

Initially, five WES recording stations were established, three for ground motion and two for the structural response of the intake tower. All detonations from B1 through C6 were monitored at these five locations. Only three stations were monitored by WES during the D-series,

two of which were at the intake tower. All recording locations are shown in Fig. 25 and described in Table 11.

Several residential buildings in the town of Viola, approximately 2,500 ft from the main experimental area, were extensively surveyed for the development of new plaster cracks and the widening of existing cracks.

Each WES recording station consisted of three velocity transducers in a triaxial array with the horizontal components oriented radially and transversely with respect to the shot locations. The velocity transducers were moving-coil geophones

Table 11. Locations of seismic recorders, Project Trinidad.

Detonation	Distance from surface ground zero (ft)					
	GM-1 (200 ft from intake tower)	GM-2 (in Viola)	GM-3 (~5000 ft east of Series B)	GM-4 (in Sopris)	SR-1 (on top floor of intake tower)	SR-2 (on foun- dation of intake tower)
B1	16,000	3400	5050	— ^a	16,000	16,000
B2	16,000	3460	5040	—	16,000	16,000
B3	16,000	3560	5160	—	16,000	16,000
B4	16,000	3570	5090	—	16,000	16,000
B5	16,000	3390	4940	—	16,000	16,000
B6	16,000	3240	4840	—	16,000	16,000
B7	16,000	3330	4850	—	16,000	16,000
B8	16,000	3170	4740	—	16,000	16,000
C1	15,500	3060	4710	—	15,500	15,500
C2	15,500	2860	4580	—	15,500	15,500
C3	15,500	2670	4480	—	15,500	15,500
C4	15,500	2490	4380	—	15,500	15,500
C5	15,500	2310	4290	—	15,500	15,500
C6	15,500	2560	4250	—	15,500	15,500
D1	—	—	—	2300	9,000	9,000
D2	—	—	—	2600	9,300	9,300
D3	—	—	—	2850	9,550	9,550
D4	—	1800	—	—	15,500	15,500

^aDashes denote that station was not recorded.

having a natural frequency of 1 Hz and 70% critical damping. The geophones were embedded in modeling clay in order to attach them to the rock or structure at each location. The signals were recorded on direct-write oscillographs. A semi-permanent installation was set up to

record signals at and near the intake tower, and portable recorders were used at the other locations. Radio communication was maintained between each recorder and Project Control at detonation times. The NOAA instrumentation, which is described in Ref. 12

Fig. 26. Peak ground motion amplitudes vs distance.

also consisted of velocity transducers arrayed triaxially.

RESULTS

The data collected during this program are tabulated in Appendix C. Motions have been expressed in terms of zero-to-peak amplitudes, and an attempt has been made to report separately the amplitudes for compressional, shear, and surface waves for all events except the B series.

The peak amplitudes recorded at the ground motion stations are presented graphically as a function of distance in Fig. 26. The straight-line representation of the data on a log-log plot is equivalent to an inverse power law relationship of the form:

$$V = KW^p R^{-n}$$

where

V = peak particle velocity

K = a constant

W = charge weight

R = distance from the detonation

p and n = empirically determined exponents.

This is the most common form of equation for empirically describing the variables involved, but it is not a physical description of attenuation.¹⁴

A number of significant results are apparent from an inspection of Fig. 26. It will be noted that the rate at which amplitudes attenuate with distance decreases as the total yield of the detonation increases. This is probably because of the relatively greater low frequency content of the seismic signal with increasing source size; i.e., increasing charge

weight, and the fact that attenuation is proportional to frequency.

The observation that the attenuation of peak amplitudes with distance depends upon total charge weight also means that the apparent weight-scaling of amplitudes will depend on the distance from the detonation. The weight scaling varied from about 0.45 at 2,500 ft to about 0.95 at 15,000 ft. A statistical analysis of all the seismic information from Project Trinidad, including the data from the Middle Course II Series, is the subject of Ref. 13. In this report the peak amplitudes were successively adjusted for weight-scaling and depth of burial until all the data points had a least squares best fit to a straight line on log-log paper. The final best-fit equation through all the data points, which was derived in Ref. 13, is:

$$V = 3.37 \times 10^5 W^{0.74} R^{-1.87} \times \exp[0.06(dob-20)]$$

where

V = peak particle-velocity, in cm/sec,

W = largest instantaneously detonated charge weight, in tons,

R = distance, in ft,

dob = scaled depth of burst, in ft/ton^{1/3}.

This equation can be used to predict peak amplitudes at the Trinidad site within a factor of two for charge weights from 1 to 100 tons, and for distances from 1 to 10 mi.

The peak particle velocities were lower than had been predicted before the beginning of the test program. The initial preshot predictions were based on previous experience with similar charge weights at other sites; however, the observed peak

amplitudes were lower by a factor of approximately five. This is believed to be primarily due to the weak and stratified nature of the rock.

A significant result of the seismic program is the marked reduction of ground shock when delays are used between charges in a row. Although this effect was well known from the extensive use of delays in quarrying, it was not known whether the technique could be used for larger scale cratering detonations. Inspection of Fig. 26 will show that the delayed five-charge rows generated seismic amplitudes virtually identical to a single 1-ton charge. This is approximately a three-fold reduction of the seismic signal generated by a simultaneously detonated row of five charges. The relatively longer delay time of 50 msec appears to have been only slightly more effective in diminishing ground shock than the 25-msec delay; however, the shorter delay was definitely advantageous from the standpoint of cratering efficiency.

The results of monitoring close-in residential structures was disappointing in the sense that no damage was observed. The peak ground motion amplitude re-

corded at a building was 1.5 cm/sec in Viola, and careful scrutiny of plaster walls failed to disclose any new cracks or the widening of pre-existing ones.

The response of the intake tower was analyzed by John A. Blume and Associates to establish ground motion criteria that would avoid detectable damage to the structure.¹⁵ The tower is a massive reinforced concrete structure about 180 ft high. Its fundamental natural period of oscillation is about 0.6 sec. Because the response of the tower to ground motion depends on the frequency content of the ground motion, and because the spectrum of ground motion depends on both charge weight and distance, it is not possible to state a simple set of criteria. For a relatively large detonation, say 300 tons, a safe level of ground motion would be about 3.5 cm/sec; however, for smaller charges of the order of 5 tons, the safety criterion would be 20 to 30 cm/sec of ground motion at the base of the tower. Peak motion recorded at the base of the tower was approximately 0.08 cm/sec, and the maximum motion recorded at the top of the tower was about 0.18 cm/sec.

Chapter 5. Airblast Measurements

SCOPE

The wide variety of cratering experiments in this project provided an excellent opportunity to acquire airblast information useful for extending the capability to predict airblast from explosive excavation projects in general. Another aspect of the airblast program was instrumentation

of various areas as a legal safeguard. Airblast overpressures were measured at ranges of a few hundred feet to several miles from the detonations.

Buried detonations in unsaturated rock give rise to two distinct airblast pressure pulses. The initial or ground-shock-induced pulse is caused by the upward spall velocity of the ground surface above

the explosion. This is followed by the gas-vent-induced pulse when the cavity gas vents to the surrounding atmosphere. The gas-vent pulse is relatively strong for shallow detonations, but is rapidly suppressed with increasing scaled depth of burial; it also lags further behind the ground-shock-induced pulse for deeper detonations. Ground shock airblast becomes dominant for deep explosions.

The amplitude of either airblast pulse is a function of range from the experiment location, type and weight of explosive, depth of burial, rock type, and the ambient atmospheric conditions. Past experience has shown that peak pressure at intermediate distances generally attenuates as $R^{-1.0}$ to $R^{-1.3}$, where R is the distance. Further, it is possible to adjust for charge size and for differences in ambient air pressure by simple scaling laws. The remaining factors; i.e., depth of burial, medium, and explosive type, are the chief influences on airblast from single-charge explosions that can be examined experimentally. Previous experiments have investigated airblast from TNT and nuclear explosives in a variety of soil and rock media.

RESULTS

Because of the volume and complexity of the data collected, only a few selected results of the airblast program are presented in this chapter. A complete summary of the observed peak overpressure is tabulated in Appendix D, and an analysis of this information accompanies the data. Reference 16 is a thorough analysis of all the airblast data.

Some of the more relevant information is presented graphically in Fig. 27, in which observed peak overpressures for selected events have been plotted against distance. Figure 27 is intended to provide a comparison between peak overpressures from a variety of detonations. Airblast amplitudes from two 1-ton detonations, Detonation B6 near optimum depth of burial and a 1-ton surface burst, are plotted to provide a frame of reference for the row-charge data. The row-charge data are from a simultaneously detonated five-charge row (C1), from a delayed five-charge row (C5), and from the delayed double-row D4 detonation. Except for the surface burst, lines with a slope of $R^{-1.2}$ have been drawn through the data points. The overpressures plotted in Fig. 27 are those recorded perpendicular to the sides of the rows, these pressures always being higher than those recorded off the ends (axial direction) of the row charges. With the exception of the data for B6, the peak pressures plotted were generated by the gas vent.

To put the plotted airblast amplitudes into some perspective, Table 12 contains criteria for damage, a matter of direct interest for explosive excavation projects.

There are several significant aspects to the information in Fig. 27. The introduction of delays between the charges in a row substantially reduces the airblast generated, as is seen by comparing C1 to C5. The detonation of the array of 44 tons of explosive in D4 generated airblast pulses that were generally lower in amplitude than those generated by a 1-ton surface burst. However, one of the recordings for D4 indicates an overpressure that approaches a 1-ton surface

Fig. 27. Peak airblast overpressures for selected Project Trinidad detonations.

Table 12. Airblast damage criteria.

Overpressure, P (mbar)	Degree of damage
2	Possible window damage, particularly to large store windows.
3	Some damage to large plate glass windows can be expected.
4.5	Some damage to average size windows can be expected.
13	Extensive damage to windows; probable damage to average wooden doors.
40	Most small casement windows smashed.
Over 40	Structural damage possible.

burst. This point is plotted in Fig. 27, and is attributed to reinforcement of the gas vent pulse from one of the two rows by the ground shock pulse from the other.

This is pointed out to illustrate the manner in which airblast pulses from arrays of charges can interact, and the fact that airblast is, in general, difficult to predict.

No window pane damage was reported for these detonations, although the nearest buildings were only 2,500 ft away. Figure 27 shows that the threshold for damage to small windows corresponds to a distance of approximately 1,000 ft from a five-charge row such as C1. At this distance, there is probably a greater probability of damage from rock missiles than from airblast.

Chapter 6. Engineering Studies of D4 Crater

INTRODUCTION

An intensive postshot investigation of the D4 crater (RR1) was conducted to determine the engineering properties of the fallback, and to determine the shaping required to bring the crater to design configuration. The investigations consisted of:

- Trenching and weighing a portion of the fallback to determine the mass density
- Applying the point-count technique¹⁷ to determine the particle gradation of the fallback
- Drilling, coring, and using the borehole camera to locate the limits of the fallback and rupture zones
- Shaping the crater by bringing the bottom to grade and dressing the slopes
- Compacting the fallback with a heavy, vibratory compactor to measure induced settlements
- Testing for the mechanical properties of the material at the University of California Richmond Laboratory. (This portion of the program, reported in Appendix E, consisted of an accurate determination of particle gradation, determining the strength and compressibility characteristics of the fallback, and ascertaining the validity of modeling a heterogeneous material of this type.)

ON-SITE INVESTIGATIVE PROGRAMS

Figure 28 shows the location of the field programs in and around the crater.

MASS DENSITY AND BULKING FACTOR

Immediately after the D4 detonation, a trench was excavated in the western portion of the crater to determine the mass density of undisturbed fallback. A relatively level area, judged to be representative of the entire crater, was selected for trenching. The front-loader used for trenching was guided with care to preclude unnecessary disturbance to the fallback. The material was removed, loaded on 5-ton dump trucks, and weighed. The volume of the material removed was determined by a detailed survey of the resulting trench.

The fallback removed from the trench weighed 372,350 lb, and the volume of the trench was 2894.4 ft³, resulting in a mass density of 128.6 lb/ft³. The bulking factor* of the fallback can be computed by comparing this density to that of the undisturbed rock. Laboratory tests of the country rock showed an average density of 156.3 lb/ft³, thus yielding a bulking factor of 1.22, a value which is consistent with data from similar experiments.¹⁸

FIELD DETERMINATION OF PARTICLE GRADATION

Because of the large dimensions of the coarse particles of the rubble from a cratering explosions, the initial particle gradation was determined by a statistical

*The bulking factor is the ratio between the in situ density of the country rock determined by coring and the mass density of the fallback. It is a valuable parameter in determining the postshot properties, balancing of cuts and fills, and estimating earth and rock moving production rates.^{20,21}

Fig. 28. Map of D4 crater showing location of postshot engineering investigations.

technique developed by Anderson,¹⁷ based on earlier work by Wolman.¹⁹ Because Anderson's technique was originally developed for nuclear detonations, which produce considerably large rock fragments, it was necessary to modify his technique. The dimensions of those particles which could be measured were obtained as specified by Anderson. In addition, representative samples of the fines were collected, air dried, and sieved in the normal fashion. The two methods can be then combined to produce a single curve; the lower limit of the point-count is faired into the upper limit of the sieving.*

*Only those particles below a conveniently measurable size were counted during the sieving.

The gradation curves obtained at both ends of the railroad cut are shown in Appendix E* where they are compared with carefully sieved samples obtained at the University of California. Results of the field technique are considered to be satisfactory and reasonable approximations of the actual grain-size distribution.

DRILLING, CORING, AND BOREHOLE PHOTOGRAPHY

Continuously cored holes were drilled to establish the limits of the fallback and rupture zones. Borehole photography was used to determine the extent of blast-induced fracturing.

*Figure E1.

Three NX core holes were drilled in the cratered area as shown in Figs. 28 and 29. Holes 1 and 2 were located at the bottom of the crater and hole 3 was located on the apparent crater lip, 100 ft from the centerline. The holes were located approximately at mid-crater.

Analysis of the core indicated 7 ft of fallback in Holes 1 and 2, a depth that contrasts with the 2 ft of fallback observed in the west end where the trench was excavated. Further investigations indicated 1 to 2 ft of fallback in the low area on the east end of the crater. This variation in the thickness of the fallback represents the presence of mounds in the bottom of the crater that appear to be randomly distributed.

The extent of blast-induced fracturing was determined from an examination of the core and from borehole photographs. The rock was highly fractured to depths of 16 to 18 ft below the ground surface at Holes 1 and 2. No blast-induced fracturing could be observed at Hole 3. Outlining the boundary of blast-induced fracturing shown in Fig. 30 was difficult because of the already fractured and weak nature of the country rock.

SHAPING OF RAILROAD CUT

Earthwork was required to shape the crater into its final design configuration; i.e., ready to accept subbase, ballast, and track. This work consisted of daylighting the ends of the crater, scaling the slopes, and leveling the bottom to subgrade elevation. A bulldozer with ripper accomplished most of the earthmoving.

Operations began with the daylighting of the east end of the crater. The loose

Fig. 29. Location of core holes in D4 crater and extent of blast-induced fracturing (cross section through Station 93+00).

Fig. 30. Dozer daylighting end of cut and bringing cut to grade.

material was pushed into the crater and the operation progressed towards the west end of the crater, cutting and filling as required. A considerable mound of material was pushed out the west end of the crater. This operation is shown in Fig. 30. Some ripping was necessary in order to daylight the ends of the crater; daylighting of the ends was not included in the experiment design.

Three working days were required to daylight the ends and bring the bottom of the crater to rough subgrade. Two additional days were spent in scaling the slopes and final leveling of the bottom of the cut. A 5-yd³ front-loader was brought in to

assist the dozer in scaling the slopes because of the difficulty in negotiating the slopes with a blade full of material. The slopes were scaled by pushing the material into the crater and spoiling it with the front loader, as shown in Fig. 31.

The area in the vicinity of Station 91+60 was somewhat troublesome because of the steepness of the crater slopes, large particle sizes, and the amount of rubble in the bottom of the crater. Several hundred cubic yards of material were removed from this area alone. Figure 32 shows the final cut configuration.

Total equipment time required was 45 dozer-hours and 16 front-loader hours. Equipment time could have been reduced substantially had the crater been daylighted by the explosion, in which case it is estimated that the cut could have been shaped in about 3 working days.

FALLBACK COMPACTION AND FIELD SETTLEMENT STUDY

Surveys were made to record any fallback settlement that might occur naturally, or might be induced by a heavy vibratory compactor. Six surface settlement

Fig. 31. Dozer scales crater slopes; front loader removes material from crater.

markers, detailed in Fig. 33, were emplaced in the undisturbed fallback. The markers were emplaced on the natural mounds and valleys of the crater bottom in order to observe settlements of different thicknesses of fallback. The locations of the markers are shown in Fig. 34.

These markers were first surveyed on 18 December 1970, and surveyed again 4 mo later on 17 April 1971. During the

Fig. 32. Finished cut.

Fig. 33. Settlement markers.

Fig. 34. Layout of settlement markers for vibratory compaction tests.

intervening 4 mo the material was subjected to 14 in. of precipitation; however, comparison of the levels showed negligible settlement during this period.

Vibratory compaction of the dressed cut started after two test panels had been laid out along the centerline, as shown in Fig. 34. Surface markers were placed in hand-excavated holes, and the displaced material was carefully replaced.

Settlement-at-depth markers were embedded in 6-in. diameter drilled holes lined with a plastic casing. A rock bit and air, rather than drilling mud or water, were used to drill these holes to minimize disturbance of the fallback. It was recognized that the vibrations from the drill bit would probably cause some unavoidable settlement in the surrounding medium. A 1-in. diameter pipe was embedded in a small quantity of grout at the bottom of the holes, and a concrete collar and steel plate were then placed over the hole. Markers were placed at 2.5 and 5-ft depths. The tops of all markers were surveyed both vertically and horizontally to 0.001 ft.

A smooth-roller vibratory compactor, illustrated in Fig. 35, made 40 passes

Fig. 35. Bros smooth-roller vibratory compactor.

over each test panel. Specifications for the BROS Model SPV-730 are as follows:

Total weight, lb	20,000
Dynamic force, lb	30,000
Vibration frequency, vpm	1,100-1,500
Drum width, in.	84
Travel speed, mph	0 to 12
Total applied force, lb	42,200

The settlement markers were surveyed for vertical displacement after 2, 5, 10, 20, and 40 passes, and for horizontal displacement after the final pass. The observed settlement of the surface is plotted against the number of passes in Fig. 36 together with representative curves of the average and the maximum settlements.

No settlement at depth was observed. Any apparent movements were well within the limits of surveying error. The lack of measurable settlement at depth probably reflects the combined effects of particle gradation, the compaction of the material falling under impact after the explosion, compaction due to the construction equipment shaping the cut, and the inability of a large vibratory compactor

Fig. 36. Surface settlement produced by vibratory compaction tests .

to appreciably affect the material at 2.5- and 5-ft depths.

The compaction portion of the field testing originally included a test in which the material was wetted before compaction. It was anticipated that this wetting of the fallback would wash the fines from between the larger particles, and weaken the larger particles, resulting in settle-

ment similar to that observed in rock-fill dams. However, the high percentage of fines and their clay nature negated this portion of the testing. The water did not percolate down through the material, but merely puddled at the surface. The results of the laboratory tests reported in Appendix E provide further insight into the wet behavior of this material.

Chapter 7. Conclusions

The single charges detonated in the B-series showed that the optimum depth of burial for 1 ton of metallized slurry (TD-2), or for 1 ton of ANFO, is approximately 18 ft. This series also indicated that the TD-2 slurry is about 50% more effective than AFNO as a cratering explosive. The relative inferiority of ANFO, however, was not substantiated by the D1 experiment in which the ANFO nearly

equalled TD-2 in cratering performance. The reason for the discrepancy between the single- and row-charge results is not clear.

The concept of enhancement, which was originally developed in a weak clay shale and which forms the basis for row-charge design, was confirmed for the Trinidad sandstones and shales and can be extended to other rock types with confidence.

The use of millisecond time delays between the charges in a row offers a promising method of reducing ground shock and airblast without incurring an unacceptable loss of row-charge cratering efficiency. In general, the seismic and airblast amplitudes generated by a delayed row-charge were approximately equivalent to what would be generated by one of the charges in the row detonated by itself. Although the two delay times of 25 and 50 msec resulted in about equal reductions of airblast and groundshock, the shorter delay is definitely preferred because it has the least effect on crater volume. It is tentatively concluded that a delay of $25 \text{ msec/ton}^{1/3}$ is appropriate for delayed row-charges.

Comparison of the simultaneously detonated double row, C6, and the D4 delayed double row demonstrates that the introduction of a delay time between the detonation of parallel row charges increases cratering performance of a double row. The delay time should be of the same order as the vent time,* which is approximately $150 \text{ msec/ton}^{1/3}$ for charges buried at optimum cratering depth.

The single and double rows along a sidehill produced relatively broad, shallow craters. The charge spacing was too wide in the D2 single row, and the performance of the explosive and the time delay between rows were questionable in the D3 double row. It is now believed that the charges in D3 were buried too deeply and too far apart, the consequence of using an incorrect value of explosive bubble energy to design the experiment.

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*The time at which the explosion gases under the rising mound of rock are vented to the atmosphere.

The final experiment, the D4 railway cut, is considered a success in all respects. A subsequent analysis of the direct costs of emplacement drilling, explosives and postshot shaping indicates that the cut was explosively excavated for approximately \$36,000. The Government estimate of the cost to accomplish the same amount of work by conventional methods, including presplitting for slope control, was approximately \$47,000.

The results of the seismic and airblast programs are important contributions to the technology. Measurement of the effects of the single- and multiple-charge detonations makes it much easier to predict these side effects for future detonations.

A number of specific conclusions can be made with regard to the engineering properties of the craters, an important aspect of explosive excavation: These conclusions are based on investigations of the D4 crater.

Cratering detonations in the heterogeneous weak-to-intermediate-strength rock at Trinidad produce rubble with a particle gradation that can be classified as a poorly graded gravel in the Unified Soil Classification System, and can also be described as a clayey gravel. The material is fragmented to the extent that necessary earthwork can be accomplished quickly and easily, with a minimum of equipment.

The D4 delayed row-charge detonation ejected enough material from the crater that the thickness of fallback material susceptible to settlement was reduced significantly. Moreover, there is considerable evidence that the fallback is favorably compacted by the impact of its

deposition. The value of relative density of 70% estimated for the Trinidad fallback in the field is almost as great as the relative densities achieved in many engineered fills (see Appendix E). It is concluded that the fallback will not be susceptible to large settlements or to stability problems, and that it will provide a stable subgrade for the railroad.

The rocks of which the fallback is composed are weakened by water, and, as a result, saturation of the material would cause settlement and would reduce the angle of internal friction by several degrees. The cohesion of the rubble, the intact horizontal bedding surrounding the cut, the wet and dry angle of internal friction, and the gentle 30-deg side slopes provide adequate assurance of continued slope stability.

The smaller particles of the fallback are softer and more highly susceptible to compression when wetted. Consequently, the amount of settlement due to wetting cannot be estimated on the basis of tests on small size specimens of "model" materials. The test results in

Appendix E do show, however, that it is possible to determine the angle of internal friction by testing model materials with grain-size curves parallel to the actual grain-size curve, provided that the specimens were compacted to the relative density of the actual fallback. The inability to estimate settlement from the behavior of the modeled material at Trinidad is valuable documentation of the media dependency of modeling materials. Higher strength and more homogeneous materials investigated by Marachi *et al.*²⁰ show much better modeling characteristics.

The rock surrounding the cut was disturbed only in the immediate vicinity, with little evidence of an extensive rupture zone. The weak, fractured, and weathered nature of the rock probably accounts for the limited extent of the rupture zone.

Finally, the point-count technique provided a reasonably accurate particle gradation curve (see Appendix E). More experience is needed in dealing with fines and their relationship to the coarse fraction of the material.

Appendix A

Drill Hole Locations, Stratigraphy and Lithology, and Material Properties Data

This appendix contains detailed information about the experimental sites. Figures A1 and A2 are topographic maps showing the location of all charges in each experiment. The stratigraphic

sections for each series, obtained from the core holes, are shown in Figs. A3 through A6, and the laboratory-determined physical properties of the rock are given in Table A1.

Fig. A1. Map showing location of core holes for B and C series and D4 railroad cut.

Fig. A2. Map showing location of emplacement and core holes for Experiments D1, D2, and D3.

Fig. A3. Stratigraphy and lithology of B series.

Fig. A4. Stratigraphy and lithology of C series.

Legend

- OVERBURDEN: Clayey soil with platy fragments of sandstone and river-run cobbles.
- SANDSTONE: Fine to medium-grained arkosic sandstone, moderate to highly fractured.
- SILTSTONE: Grey-green siltstone, highly fractured.
- SHALE: Grey to black silty shale, highly fractured.

Fig. A5. Stratigraphy and lithology of Experiments D1, D2, and D3.

Legend

- OVERBURDEN: Clayey soil with platy fragments of sandstone and river-run cobbles.
- SANDSTONE: Fine to medium-grained arkosic sandstone, moderate to highly fractured.
- SILTSTONE: Grey-green siltstone, highly fractured.
- SHALE: Grey to black silty shale, highly fractured.
- COAL: Soft bituminous coal, very highly fractured.

Fig. A6. Stratigraphy and lithology of D4 railroad cut.

Table A1. Results of tests of B-series rock cores.

Hole number	Depth (ft)	Water content ^a (%)	Dry density (lb/ft ³)	Grain specific gravity	Porosity (%)	Compressive strength (psi)	Modulus of elasticity (10 ⁶ psi)	Description and remarks
B3	19.1-19.8	3.0	150.1	2.70	10.7	4563	0.4-1.3	Light gray sandstone with hairline to 1/16 in. shale seams.
B3	19.8-20.8	3.8	151.3	2.70	10.4	5937 ^b	1.3	Light gray sandstone, fine grained.
B3	21.0-22.9	3.2	156.5	2.70	7.1	1739	0.23	Dark gray silty sandstone, very fine grained.
B8	13.2-13.5	5.1	149.2	2.70	11.5	1833 ^{b,c}	0.80 ^c	Tan siltstone with random orientated shale stringers. Free water was observed on the surface of the test specimen while under compression.
B8	15.8-17.0	2.7	156.7	2.71	7.4	5159	1.5	Light gray sandstone, fine grained.
B8	21.5-22.2	4.4	146.0	2.70	13.3	1027 ^b	0.072	Gray sandy siltstone with shale seams to 1 in. wide. Free water was observed on the surface of the test specimen while under compression.
B8	24.8-27.2	2.0	106.1	1.82	6.6	1070 ^b	0.23	Coal.
B8	27.0-28.4	1.2	160.8	2.72	5.3	493	0.33	Gray sandy siltstone with irregular shale and coal seams hairline to 2 in. wide, and partly open fractures. Failure occurred along a high angle, partly open fracture.

^aWater content was determined on fragments remaining from compression test.

^bValues for unconfined compressive strength have been adjusted for height-diameter ratio per ASTM C-42.

^cDiameter of test specimen was not uniform due to drilling action.

Table A2. Results of tests of C-series rock cores.

Hole number	Depth (ft)	Water content (%)	Dry density (lb/ft ³)	Grain specific gravity	Porosity (%)	Compressive strength ^a (psi)	Modulus of elasticity (10 ⁶ psi)	Description and remarks
C2C	2.5 - 3.0	2.6	150.2	2.68	10.2	—	—	Sandstone, tan, fractured, thin layer of brown clay along fractures.
C2C	10.9 -12.1	2.1	159.5	2.66	4.0	6420	3.2	Sandstone, tan, horizontal fractures at 11.5 ft.
C2C	12.1 -12.9	2.6	160.4	2.74	6.2	1370	0.38	Sandstone, fine-grained, gray, partly open fractures.
C2C	13.1 -15.0	2.9	152.9	2.69	8.9	7260	0.5-1.3	Siltstone, gray, numerous hairline to 1/8 in. shale seams from 13.1-13.8 ft.
C2C	17.25-18.2	4.3	138.1	2.46	10.1	1290	0.14	Top 6 in. transition zone from coal to gray siltstone separated at 18.1 and 19.35 ft, 1 in. shale band at 18.9-19.0 ft, partly open vertical fracture from 19.0-19.3 ft, partly open fractures from 19.6-19.9 ft, carbonaceous stringers from 18.1-18.5 ft.
C2C	18.2 -19.9	4.2	150.8	2.69	10.2	1290	0.13	Dark gray, highly carbonaceous siltstone, healed vertical fracture from 21.7-22.5 ft.
C2C	21.7 -22.78	2.8	156.3	2.71	7.6	3260	0.75	Dark gray, highly carbonaceous siltstone, healed vertical fracture from 21.7-22.5 ft.
C4C	10.34-10.98	2.8	153.6	2.67	7.9	6380	1.6	Sandstone, tan, with irregular shale seams hairline to 1/16 in.
C4C	21.0 -22.7	2.8	150.9	2.69	10.1	7340	0.7-1.2	Transition from tan sandstone to gray sandstone, high angle fracture from 21.0-21.8 ft.
C6C	20.0 -20.72	9.2	78.1	1.50	16.6	—	—	Coal, fractured.
C6C	21.2 -22.44	2.1	157.0	2.72	7.5	6350	1.0-1.5	Transition from tan sandstone to gray sandstone with irregular shale seams up to 1 in. Partially opened horizontal fracture at 22.0 ft.

^aValues for unconfined compressive strength have been adjusted for height-diameter ratio per ASTM C-42.

Table A3. Results of tests of D-series rock cores.

Hole number	Depth (ft)	Water content ^a (%)	Dry density (lb/ft ³)	Grain specific gravity	Porosity (%)	Compressive strength ^b (psi)	Modulus of elasticity (10 ⁶ psi)	Description and remarks
D1E	3.8- 5.1	4.1	144.6	2.69	14	3608	0.65	Sandstone, light brown, intersecting high angle fractures from 3.8-4.5 ft.
	5.6- 6.5	4.1	149.4	2.66	10	2947	0.41	Sandstone, light brown, hard.
	9.7-11.3	5.9	138.9	2.69	17	883	0.12	Sandstone, light brown, 60 deg fracture from 9.7-10.1 ft; 45 deg incipient fracture 10.3-10.7 ft.
	12.1-13.7	2.8	150.5	2.69	11	2163	0.31	Sandstone, light gray, changing to light brown at 12.8 ft; numerous incipient fractures.
	21.4-22.0	7.3	138.7	2.71	18	460	0.13	Shale, light gray, hard.
	28.6-29.6	4.9	145.4	2.73	14	873	0.25	Shale, light gray, hard, approximate 45 deg incipient fracture top to bottom.
D3D	11.9-12.8	2.1	155.1	2.70	8	8272	2.35	Sandstone, very light brown, very fine-grained, hard. Very thin layers of shale at both ends of sample.
	13.0-14.3	3.5	148.4	2.65	10	530	0.24	Siltstone, light gray, much-fractured.
	18.7-19.5	3.0	152.7	2.62	7	1373	0.67	Siltstone, shaly, light gray, horizontal separation planes at 18.9 and 19.1 ft.
	21.5-22.5	4.6	148.9	2.66	11	1074	0.25	Siltstone, shaly, light gray, hard. Horizontal slickensided fracture at 22.0 ft.
D4A	12.0-12.6	3.3	151.9	2.63	7	3055	0.50	Sandstone, light gray, fine-grained; numerous horizontal separation planes.
	15.5-16.6	5.0	138.9	2.66	16	3853	0.74	Sandstone, light brown, hard.
	21.2-22.0	3.8	151.3	2.71	10	2000	1.04	Sandstone, light brown, hard; 60 deg fracture for compression test.
	22.6-24.0	2.4	155.4	2.65	6	6824	1.6	Sandstone, fine-grained, light gray, hard; 45 deg fracture 23.1-22.8 ft.
	28.1-28.3	2.7	152.2	2.69	9	— ^c	— ^c	Siltstone, light gray, dry, hard; too badly fractured for compression test.
	28.3-28.5	4.4	148.0	2.71	12	— ^c	— ^c	Siltstone, shaly, light gray, moist; too badly fractured for compression test.
	32.4-33.1	6.6	143.5	2.71	15	510	0.09	Shale, gray, moist; many thin horizontal separation planes.
	33.1-33.8	4.3	149.4	2.70	12	898	0.34	Shale, light gray, dry, hard; numerous horizontal separation planes.
D4B	6.0- 6.65	3.6	154.3	2.66	6	— ^c	— ^c	Siltstone, gray, hard; very badly fractured.
	15.3-15.9	3.3	150.5	2.64	9	4140	2.0	Sandstone, light brown, hard; 1/2-in. shale seam removed from bottom.
	18.85-19.5	7.0	140.0	2.72	17	739	0.11	Shale, gray, moist; numerous slickensided separation planes.
D4C	15.9-15.5	2.6	152.1	2.68	9	2780	0.60	Sandstone, light brown, fine-grained, hard.
	18.9-19.7	2.6	151.3	2.69	10	4950	1.3	Sandstone, light brown, hard.
	19.7-20.3	—	—	—	— ^c	— ^c	— ^c	Sandstone, light brown, hard. Very thin shale seams at 19.8 and 19.9 ft.
	22.3-23.9	3.8	148.2	2.69	12	4200	0.76	Sandstone, light brown with light gray band from 22.5-23.0 ft; horizontal separation planes at 23.1, 23.4, and 23.6 ft. Compression specimen taken from 23.2-23.8 ft.
	29.2-29.9	3.7	150.5	2.69	11	710	0.06	Siltstone, light gray, hard; fractures at 29.3, 29.5, and 29.7 ft.
	31.2-31.8	2.1	158.7	2.69	6	2460	0.56	Siltstone, light gray, dry, hard; 45 deg separation plane 31.4-31.7 ft.
	32.0-32.7	1.9	154.2	2.67	7	7169	0.77	Siltstone, light gray, fine-grained, hard; numerous thin, shale seams. Horizontal separation plane at 32.7 ft.
	32.7-33.5	2.4	154.4	2.67	7	4245	0.65	Sandstone, light gray, fine-grained, hard; more and thicker layers of shale.

^aWater content was determined on fragments remaining from compression tests.^bValues for unconfined compressive strength have been adjusted for height-diameter ratio per ASTM-C 42.^cNot tested.

Appendix B

Crater Profiles and Cross Sections

This appendix contains the cross sections and profiles for all of the B-series and C-series craters. Figure B1 explains the meaning of the terms used in standard crater nomenclature. Each of the single-charge craters was surveyed along two orthogonal sections, as shown in Figs. B2

through B5. The row craters were cross-sectioned at selected, representative locations and were also profiled along the centerline through the charges. The survey data are shown in Figs. B6 through B8. The average widths and depths of the row craters are shown on the drawings.

Nomenclature which applies only to single-charge craters

R_a - Radius of apparent crater measured at original ground surface datum

R_{al} - Radius of apparent lip crest

R_{eb} - Radius of outer boundary of continuous ejecta

D_a - Maximum depth of apparent crater below and normal to original ground surface

Nomenclature which applies only to row craters

W_a - Width of apparent linear crater measured at original ground surface datum

W_{al} - Width of apparent lip crest

W_{eb} - Width of outer boundary of continuous ejecta

D_{ar} - Depth of apparent row crater

Nomenclature and definitions which apply to both single-charge and row craters

H_{al} - Apparent crater lip crest height above original ground surface

V_a - Volume of apparent crater below original ground surface

V_{al} - Volume of apparent lip

V_t - Volume of true crater below original ground surface

DOB - Depth of burst

ZP - Zero Point-effective center of explosion energy

SGZ - Surface Ground Zero (point on surface vertically above ZP)

NSP - Nearest Surface Point (point on surface nearest ZP; same as SGZ for horizontal surface)

Fig. B1. Crater nomenclature.

Fig. B2. Cross sections of Craters B1 and B2.

Fig. B3. Cross sections of Craters B3 and B4.

Fig. B4. Cross sections of Craters B5 and B6.

Fig. B5. Cross sections of Craters B7 and B8.

Fig. B6. Longitudinal profiles and representative cross sections for Rows C1 and C2.

Fig. B7. Longitudinal profile and representative cross sections for Row C3.

Fig. B8. Longitudinal profiles and representative cross sections for Rows C4 and C5.

Appendix C Seismic Data

This appendix tabulates all values of peak particle velocity recorded during Project Trinidad. The locations of the recording stations and the station-shot distances are given in Chapter 4.

Table C1. Maximum recorded particle velocities for B-series.
(All values to be multiplied by 10^{-3} .)

Station	Component	ANFO			AANS (TD-2)				
		B1 (cm/sec)	B2 (cm/sec)	B3 (cm/sec)	B4 (cm/sec)	B5 (cm/sec)	B6 (cm/sec)	B7 (cm/sec)	B8 (cm/sec)
GM-1	Vertical	2.8	3.7	3.4	4.8	5.7	— ^a	4.9	— ^a
	Radial	2.3	1.6	3.2	2.2	3.0	— ^a	2.4	— ^a
	Transverse	2.3	4.1	4.3	2.2	4.2	— ^a	2.0	— ^a
GM-2	Vertical	85	75	85	95	115	100	120	160
	Radial	120	110	130	120	170	160	140	210
	Transverse	90	60	90	50	70	100	110	150
GM-3	Vertical	38	41	46	48	63	50	50	68
	Radial	18	20	26	19	27	25	20	30
	Transverse	24	28	26	20	37	25	24	42
SR-1	Vertical	9.0	4.0	3.0	5.6	8.0	— ^a	7.5	— ^a
	Radial	7.0	8.5	7.0	9.2	17	— ^a	14	— ^a
	Transverse	9.0	7.0	8.0	4.0	2.0	— ^a	8.0	— ^a
SR-2	Vertical	2.5	3.3	2.5	3.7	4.8	— ^a	4.5	— ^a
	Radial	2.4	2.1	3.7	2.5	3.2	— ^a	3.0	— ^a
	Transverse	2.4	3.8	3.7	2.0	4.0	— ^a	2.5	— ^a

^aUnreliable.

Table C2. Maximum recorded particle velocities for C1, C2, C3.
(All values to be multiplied by 10^{-3} .)

Station	Component	C1			C2			C3		
		Compressional (cm/sec)	Shear (cm/sec)	Surface (cm/sec)	Compressional (cm/sec)	Shear (cm/sec)	Surface (cm/sec)	Compressional (cm/sec)	Shear (cm/sec)	Surface (cm/sec)
GM-1	V	9.5	7.0	17	10	8.5	16	15	12	25
	R	5.0	6.0	7.5	5.5	12	8.2	8.5	19	10
	T	4.0	11	9.0	3.5	14	10	5.0	12	14
GM-2	V	80	100	340	120	150	450	230	160	660
	R	180	400	400	250	310	470	460	430	540
	T	80	270	200	100	400	120	200	480	210
GM-3	V	73	85	170	75	100	150	90	100	225
	R	60	82	85	70	70	85	85	55	60
	T	25	75	90	30	85	75	20	85	95
SR-1	V	22	— ^a	22	25	26	17	32	30	23
	R	9.0	— ^a	37	9.0	— ^a	38	10	— ^a	57
	T	5.0	15	18	7.0	— ^a	25	7.0	— ^a	36
SR-2	V	9.5	— ^a	16	7.8	— ^a	15	11	— ^a	20
	R	8.2	— ^a	10	7.5	— ^a	12	12	19	14
	T	5.5	12	8.3	7.5	20	9.0	9.0	— ^a	14

^aUnreliable.

Table C3. Maximum recorded particle velocities for C4, C5, C6.
(All values to be multiplied by 10^{-3}).

Station	Component	C4			C5			C6		
		Compressional (cm/sec)	Shear (cm/sec)	Surface (cm/sec)	Compressional (cm/sec)	Shear (cm/sec)	Surface (cm/sec)	Compressional (cm/sec)	Shear (cm/sec)	Surface (cm/sec)
GM-1	V	4.1	1.8	4.1	3.3	3.0	6.5	16	16	35
	R	2.0	3.1	2.0	2.0	3.3	3.9	9.0	28	15
	T	1.2	3.0	1.7	1.5	3.4	4.1	7.0	15	13
GM-2	V	40	50	150	— ^a	— ^a	— ^a	250	250	650
	R	80	120	130	— ^a	— ^a	— ^a	580	520	700
	T	40	140	110	— ^a	— ^a	— ^a	140	700	300
GM-3	V	32	32	47	27	60	45	130	160	310
	R	25	18	17	30	35	20	130	130	80
	T	8.0	15	20	10	18	25	30	100	110
SR-1	V	9.0	5.5 ^b	7.5	8.0	11 ^b	13	38	— ^b	50
	R	3.0	— ^b	9.0	3.5	— ^b	21	14	25 ^b	47
	T	3.0	— ^b	9.0	1.0	— ^b	8.5	7.0	— ^b	44
SR-2	V	2.3	— ^b	3.4	2.5	— ^b	6.4	12	— ^b	37
	R	3.8	— ^b	2.9	3.9	— ^b	5.4	13	25 ^b	21
	T	2.4	3.1	1.8	4.0	5.0	3.7	11	— ^b	17

^aData not recorded.

^bUnreliable.

Table C4. Maximum recorded particle velocities for D series.
(All values to be multiplied by 10^{-3}).

Station	Component	D1			D2			D3			D4		
		Compressional (cm/sec)	Shear (cm/sec)	Surface (cm/sec)	Compressional (cm/sec)	Shear (cm/sec)	Surface (cm/sec)	Compressional (cm/sec)	Shear (cm/sec)	Surface (cm/sec)	Compressional (cm/sec)	Shear (cm/sec)	Surface (cm/sec)
GM-1	V	8.5	62	54	6.0	40	46	8.0	92	82	16	28	60
	R	8.9	33	23	7.0	26	22	6.0 ^a	55	48	12 ^a	40	25
	T	3.3	18	6.0	3.0	51	11	— ^b	92	46	— ^a	40	20
GM-2	V	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	400	— ^a	1500
	R	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	1200	— ^a	1200
	T	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	— ^b	600	— ^a	800
GM-4	V	130	70	300	50	200 ^a	480	100	— ^a	400	— ^b	— ^b	— ^b
	R	100	280	520	70	— ^a	700	50	— ^a	870	— ^b	— ^b	— ^b
	T	50	280	700	40	— ^a	430	— ^a	— ^a	320	— ^b	— ^b	— ^b
SR-1	V	20	87 ^a	90	20 ^a	60	90	30 ^a	175	160	— ^a	— ^a	70
	R	6.0	— ^a	92	— ^a	60	95	— ^a	80	180	— ^a	— ^a	110
	T	4.0	— ^a	18	— ^a	60	50	— ^a	120	100	— ^a	100	100
SR-2	V	7.3	61	48	8.0	45	45	7.0	88	83	20	28	60
	R	6.5	27	36	7.0	28	31	7.0	70	60	13	33	25
	T	5.0	20	17	6.0	47	17	6.0	103	40	10	37	13

^aUnreliable.

^bData not recorded.

Appendix D Airblast Data

The observed peak overpressures for Project Trinidad are summarized in Tables D1 through D4, together with an analysis of the data. The data have been

tabulated in the following format: first, the name of the experiment is given, followed by the charge weight, type of explosive, and depth of burial (DOB, in

Table D1. Close-in airblast observations for Detonations B1 through B8 (single-charges).
Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar

Detonation	Explo- sive	DOB (ft)	Source	Observed data		Data scaled to 1 ton and 1000 mbar		
				Distance, R(ft)	Peak overpressure ΔP (psi)	$R_s \left(\frac{\text{ft}}{\text{ton}^{1/3}} \right)$	ΔP_s (mbar)	f
B1 (1 ton)	ANFO	15.2	Ground shock	400	0.067 ^a	373.0	5.71 ^a	0.0776 ^a
				900	0.021 ^a	839.0	1.79 ^a	0.0643 ^a
				2000	0.0088 ^a	1864.0	0.75 ^a	0.0703 ^a
			Gas vent	400	0.64	373.0	54.6	0.742
				900	0.18	839.0	15.3	0.550
				2000	0.076	1864.0	6.48	0.608
B2 (1 ton)	ANFO	18.0	Ground shock	850	0.0072	792.0	0.614	0.0206
				2000	0.00307	1864.0	0.262	0.0246
				850	0.0119	792.0	1.02	0.0342
			Gas vent	2000	0.0045	1864.0	0.383	0.0359
				230	0.041	214.0	3.49	0.0244
				720	0.0105	672.0	0.894	0.0246
B3 (1 ton)	ANFO	19.7	Ground shock	2020	0.00416	1883.0	0.355	0.0338
				230	0.255	214.0	21.7	0.151
				720	0.082	672.0	6.98	0.192
			Gas vent	2020	0.0332	1883.0	2.83	0.269
				350	0.044	326.0	3.75	0.0434
				1000	0.015	932.1	1.28	0.0523
B4 (1 ton)	TD-2	15.9	Ground shock	2000	0.0063	1864.2	0.537	0.0502
				350	0.322	326.0	27.4	0.317
				1000	0.101	932.1	8.61	0.352
			Gas vent	2000	0.0373	1864.2	3.18	0.298
				295	0.057	275.0	4.86	0.0459
				810	0.021	755.0	1.79	0.0568
B5 (1 ton)	TD-2	18.6	Ground shock	1845	0.007	1720.0	0.596	0.0508
				295	0.088	275.0	7.50	0.0708
				810	0.0335	755.0	2.85	0.0903
			Gas vent	1845	0.0123	1720.0	1.05	0.0896
				163	0.0705	152.0	6.00	0.0278
				510	0.0260	475.0	2.215	0.0403
B6 (1 ton)	TD-2	20.9	Ground shock	1670	0.0079	1556.0	0.673	0.0507
				163	0.0556	152.0	4.74	0.0220
				510	0.0262	475.0	2.23	0.0406
			Gas vent	1670	0.0064	1556.0	0.545	0.0411
				275	0.04?	256.0	3.41?	0.0294?
				1630	0.00446	1520.0	0.380	0.0279
B7 (1 ton)	TD-2	22.6	Ground shock	275	0.074	256.0	6.30	0.0543
				1630	0.0149	1520.0	1.27	0.0933
				140	0.0528	130.5	4.50	0.0174
			Gas vent	460	0.0190	429.0	1.62	0.0261
				835	0.0070	778.0	0.596	0.0195
				140	0.0105	130.5	0.895	0.00346
B8 (1 ton)	TD-2	28.1	Ground shock	460	0.0046	429.0	0.392	0.00631
				835	0.00133	778.0	0.113	0.00371
				835	0.00133	778.0	0.113	0.00371

^a May be a primacord spike rather than the true ground-shock-induced peak overpressure pulse from the detonation.

Table D2a. Close-in airblast observations for Detonations C1 and C2 (row-charges).
Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar

Detonation	Source	Azimuth	Observed data		Data scaled to 1 ton and 1000 mbar		
			Distance, R(ft)	Peak overpressure, ΔP (psi)	$R_s \left(\frac{\text{ft}}{\text{ton}^{1/3}} \right)$	ΔP_s (mbar)	f
C1	Ground shock	$\perp^a$	392	0.128	365.0	10.90	0.144
			1525	0.0134	1420.0	1.14	0.077
			3360	0.00842	3130.0	0.718	0.125
	(five 1-ton charges of TD-2 buried at 18 ft, spaced at 32 ft)	$\parallel^b$	302	0.093	281.0	7.92	0.0765
			1000	0.027	932.1	2.30	0.0941
			3171	— ^c	2958.0	—	—
		$\perp$	392	0.181	365.0	15.4	0.204
			1525	0.029	1420.0	2.48	0.168
			3360	0.0164	3130.0	1.397	0.244
		$\parallel$	302	0.152	281.0	12.95	0.125
			1000	0.051	932.1	4.35	0.178
			3171	— ^c	2958.0	—	—
C2	Ground shock	$\perp$	400	0.137	373.0	11.67	0.159
			1515	0.0131 ^d	1412.0	1.116	0.075
			3360	—	3130.0	—	—
	(five 1-ton charges of TD-2 buried at 20.4 ft, spaced at 25 ft)	$\parallel$	500	0.039	466.0	3.32	0.0592
			1350	0.010 ^e	1259.0	0.852	0.0499
			2985	—	2780.0	—	—
		$\perp$	400	0.093	373.0	7.92	0.108
			1515	0.0131 ^d	1412.0	1.21	0.0814
			3360	— ^d	3130.0	—	—
		$\parallel$	500	0.039	466.0	3.32	0.0592
			1350	0.0115 ^e	1259.0	0.98	0.0574
			2985	— ^e	2780.0	—	—

^a $\perp$ - perpendicular to alignment of row.

^b $\parallel$ - parallel to and off the end of the row.

^cTransmitter drift.

^dRecord noisy.

^eRecord lost.

feet). For row-charge events, the row configuration, spacing and delays (if any) between charges in the row, number of charges, and charge weight are also specified. The next column identifies the source of the airblast pulse (ground-shock-induced or gas-vent-induced). Next, for row-charge events only, the direction in which the airblast pulse was measured is given [perpendicular to row axis ($\perp$) or off the end of the row ($\parallel$)]. The succeeding two columns list the distance R (in feet) from the detonation to a given observed peak overpressure ΔP (in psi), ΔP in this case referring to

peak excess above the local ambient pressure. Most of the measured overpressures are average values from two separate gages at the same location. Both the ground-shock and gas-vent peak overpressures are listed (in successive sections of the table) where available. Overpressures for all row-charge detonations were measured in at least two different directions, perpendicular to the row ($\perp$ to row) and off the end of the row ($\parallel$ to row). The delayed row-charges have measurements along three directions: perpendicular to the row, of the starting end ($\parallel_S$), and off the final end ($\parallel_F$) of the

Table D2b. Close-in airblast observations for Detonations C3 and C4 (row-charges).
Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar

Detonation	Source	Azimuth	Observed data		Data scaled to 1 ton and 1000 mbar		
			Distance, R(ft)	Peak overpressure, ΔP (psi)	$R_s \left(\frac{\text{ft}}{\text{ton}^{1/3}} \right)$	ΔP_s (mbar)	f
C3 (seven 1-ton charges of TD-2 buried at 23.5 ft, spaced at 18 ft)	Ground shock	⊥	349	0.105	325.0	8.94	0.103
			1530	0.0175	1425.0	1.49	0.101
			3360	0.0079	3130.0	0.673	0.117
			461	0.039/0.063 ^a	430.0	3.32/5.37 ^a	0.0536/ 0.0866 ^a
	Gas vent		1160	0.0124/0.021 ^a	1080.0	1.057/1.79 ^a	0.0516/ 0.0873 ^a
			2791	0.0048/0.0067 ^a	2600.0	0.409/0.571 ^a	0.0572/ 0.0798 ^a
		⊥	349	0.052	325.0	4.43	0.051
			1530	0.0133	1425.0	1.133	0.077
			3360	0.0049	3130.0	0.418	0.073
			461	0.0291	430.0	2.480	0.040
			1160	0.0114	1080.0	0.971	0.0474
			2791	0.0045?	2600.0	0.383?	0.0536?
C4 (five 1-ton charges of TD-2 buried at 20.4 ft, spaced at 25 ft, 0.05-sec delay between charges)	Ground shock	⊥	318	0.032	296.0	2.73	0.0282
			1525	0.0052	1420.0	0.443	0.0299
	Gas vent	^b _S	500	0.023	466.0	1.96	0.0349
			2610	0.0031	2430.0	0.264	0.0340
		^c _F	1005	0.0107 ^d	936.5	0.912	0.0375
			3000	—	2800.0	—	—
		⊥	318	0.104	296.0	8.86	0.0914
			1525	0.0212	1420.0	1.806	0.122
		^b _S	500	0.0630	466.0	5.36	0.0954
			2610	0.0129	2430.0	1.10	0.142
		^c _F	1005	0.0399 ^d	936.5	3.40	0.140
			3000	—	2800.0	—	—

^aTwo values given because signal showed double peak.

^b||_S = off end of row at which delay sequence began; i.e., starting end.

^c||_F = off end of row at which delay sequence ended; i.e., final end of two values given because signal showed double peak.

^dNo signal.

row. For the simultaneously detonated Row D1, measurements were made perpendicular to the row uphill ($\perp_U$), perpendicular to the row downhill ($\perp_D$), and off one end of the row.

In order to eliminate dependence on charge weight and the effects of local ambient pressure, ranges and overpressures must be scaled to a consistent system. In this instance, all data are scaled to a yield of 1 ton and an ambient pressure of 1,000 mbar. The conversion to scaled points (R_s , ΔP_s) is given by:

$$\Delta P_s = \Delta P \frac{1000}{P_0}$$

$$R_s = R \left[\frac{P_0}{1000} \frac{1}{W} \right]^{1/3}$$

where P_0 = ambient pressure (mbar) and W = charge weight (tons). Using P_0 = 810 mbar and W = total charge weight (or mean individual charge weight for row events), all the observed data points (R , ΔP) were scaled to (R_s , ΔP_s). The scaled values for each experiment are also compiled in Table D1, with the

Table D2c. Close-in airblast observations for Detonations C5 and C6 (row-charges).

Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar

Detonation	Source	Azimuth	Observed data		Data scaled to 1 ton and 1000 mbar		
			Distance, R (ft)	Peak overpressure, ΔP (psi)	$R_s \left(\frac{\text{ft}}{\text{ton}^{1/3}} \right)$	ΔP_s (mbar)	f
C5 (five 1-ton charges of TD-2 buried at 20.4 ft, spaced at 25 ft, 0.025-sec delay between charges)	Ground shock	$\perp$	400	0.024	373.0	2.044	0.0279
			1535	0.0070	1430.0	0.596	0.0408
		$\parallel_S$	500	0.0183	466.0	1.56	0.0278
			2430	0.0054	2263.0	0.46	0.0544
	Gas vent	$\parallel_F$	595	0.044	554.0	3.75	0.082
			1185	0.0258	1105.0	2.20	0.110
		$\perp$	400	0.047	373.0	4.00	0.0546
			1535	0.014	1430.0	1.193	0.0816
			500	0.0346/0.029 ^a	466.0	2.95/2.47 ^a	0.0525/ 0.0439 ^a
			2430	0.0089/0.0072 ^a	2263.0	0.758/0.614 ^a	0.0897/ 0.0727 ^a
		$\parallel_F$	595	0.042	554.0	3.58	0.0784
			1185	0.0274	1105.0	2.335	0.117
C6 (two parallel rows of five 1-ton charges of TD-2, 39-ft separation between rows; charges buried at 20.4 ft, spaced at 25 ft)	Ground shock	$\perp$	485	0.160?	452.0	13.63	0.234
			1110	0.041	1035.0	3.49	0.162
			2720	0.0203	2534.0	1.73	0.235
	Gas vent	$\parallel$	428	0.080+	399.0	6.82	0.100
			1690	0.0211	1575.0	1.80	0.138
			3700	0.0092	3450.0	0.784	0.154
		$\perp$	485	0.306? ^b	452.0	26? ^b	0.45? ^b
			1110	0.098/0.051 ^a	1035.0	8.35/4.35 ^a	0.387/ 0.201 ^a
			2720	0.048/0.028 ^a	2534.0	4.09/2.39 ^a	0.556/ 0.325 ^a
		$\parallel$	428	0.147/0.152 ^a	399.0	12.5/13.0 ^a	0.184/ 0.191 ^a
			1690	0.0328/0.0476 ^a	1575.0	2.79/4.05 ^a	0.214/ 0.311 ^a
			3700	0.0158/0.0203 ^a	3450.0	1.35/1.73 ^a	0.265/ 0.340 ^a

^aTwo values given because signal showed double peak.^bLarger of two peaks; calibration unstable, value uncertain.

scaled overpressures ΔP_s expressed in mbar (1.0 psi = 69 mbar).

Using the scaled data, it is possible to compare airblast from experiments with different explosives or at different depths of burial. A convenient means of accomplishing this comparison is the relating of all airblast data to an arbitrary standard. One useful standard for comparison is a straight line of slope $R_s^{-1.2}$ in a log-log plot of ΔP_s vs R_s .²² An arbitrary $R_s^{-1.2}$ line is chosen through the point ($R_s = 900 \text{ ft/ton}^{1/3}$, ΔP_s

= 25.5 mbar). All measured overpressures are related to this standard line by a transmission factor, f:

$$f(\text{at } R_s) = \frac{\text{Measured } \Delta P_s(\text{at } R_s)}{\text{Standard line } \Delta P_s(\text{at } R_s)}$$

Separate values of f are assigned to the phenomenon of ground-shock-induced airblast (f_{gs}) and the airblast resulting from gas venting (f_{gv}).

The transmission factor will be a function of R_s , scaled depth of burial,

Table D3. Close-in airblast observations for Detonations D1 through D3 (row-charges).
Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar

Detonation	Source	Observed data			Data scaled to 1 ton and 1000 mbar				
		Azimuth	Distance, R(ft)	Peak overpressure, ΔP (psi)	$R_s \left(\frac{\text{ft}}{\text{ton}^{1/3}} \right)$	ΔP_s (mbar)	f		
D1 (nine charges of ANFO, charge size 200 lb to 2000 lb, average 1090 lb, mean depth of burial 23.9 ft/ton ^{1/3} , mean spacing 15.9 ft/ton ^{1/3}) ^c	Ground shock	$\perp^a$	843	0.084	962.0	7.16	0.303		
			1482	0.0227	1690.0	1.935	0.161		
		$\perp^b$	770	0.076	878.0	6.48	0.246		
			1900	0.0128	2170.0	1.09	0.123		
	Gas vent	$\parallel$	700	0.0232	799.0	1.976	0.0672		
			3280	0.0048	2740.0	0.409	0.0886		
		$\perp^U$	843	0.005	962.0	0.426	0.0181		
			1482	0.0013	1690.0	0.111	0.0093		
		$\perp^D$	770	0.002	878.0	0.170	0.0065		
			1900	0.001	2170.0	0.085	0.0096		
		$\parallel$	700	0.0047	799.0	0.401	0.0136		
			3280	0.0013	3740.0	0.111	0.0240		
D2 (five 1-ton charges of TD-1, buried at 17.7 ft, spaced at 32 ft)	Ground shock	$\perp$	1000	0.0606	932.1	5.16	0.211		
			3210	0.0196	2990.0	1.68	0.278		
		$\parallel$	1020	0.0460	951.0	3.92	0.164		
			2240	0.0170	2090.0	1.45	0.156		
			3740	0.0128	3490.0	1.09	0.217		
			1000	0.179	932.1	15.25	0.624		
	Gas vent	$\perp$	3210	0.0411	2990.0	3.50	0.579		
			1020	0.0350	951.0	2.98	0.125		
		$\parallel$	2240	0.0135	2090.0	1.15	0.124		
			3740	0.00884	3490.0	0.753	0.150		
		D3 (two-paral- lel rows, each six charges of IR10; down- hill row: 1- ton charges buried at 19.1 ft, spaced at 35 ft) (uphill row: 2-ton charges buried at 24.4 ft, spaced at 35 ft, 40-ft separa- tion and 0.25-sec delay between the two rows)	Ground shock (1-ton row)	$\perp$	1000	0.05	932.1	4.26	0.174
					3210	0.0156	2990.0	1.33	0.220
$\parallel$	720			0.0195	671.0	1.66	0.046		
	2220			0.0067	2070.0	0.571	0.061		
Gas vent (1-ton row)	$\perp$		3815	0.00328	3555.0	0.279	0.057		
			1000	0.0653	932.1	5.56	0.228		
	$\parallel$		3210	0.0210	2990.0	1.79	0.296		
			720	0.0526	671.0	4.48	0.123		
Ground shock (2-ton row)	$\perp$		2220	0.0185	2070.0	1.576	0.168		
			3815	0.0088	3555.0	0.750	0.153		
	$\parallel$		1000	— ^d	740.0	— ^d	— ^d		
			3210	—	2375.0	—	—		
		$\parallel$	720	0.0441	533.0	3.76	0.0785		
			2220	0.186	1643.0	1.585	0.128		
		Gas vent (2-ton row)	$\perp$	3815	0.00938	2820.0	0.799	0.123	
				1000	0.0579	740.0	4.93	0.153	
	$\parallel$	3210	0.0235	2375.0	2.00	0.251			
		720	0.0498	533.0	4.24	0.0885			
		$\parallel$	2220	0.0203	1643.0	1.73	0.139		
			3815	0.01035	2820.0	0.882	0.136		

^a $\perp^U$ - perpendicular to row, uphill side.

^b $\perp^D$ - perpendicular to row, downhill side.

^cWeighted by individual charge yields to overemphasize the larger charges; this weighting has almost no effect on the data reduction. Weighting not normally used in prediction procedures.

^dUnidentifiable; coincides with first negative phase from 1-ton row.

Table D4. Close-in airblast observations for Detonation D4 (row-charges).

Altitude $\approx$ 6200 ft AMSL; ambient pressure $\approx$ 810 mbar

Detonation	Source	Azimuth	Observed data		Data scaled to 1 ton and 1000 mbar	
			Distance, R(ft)	Peak overpressure, ΔP (psi)	$R_s \left(\frac{\text{ft}}{\text{ton}^{1/3}} \right)$	P_s (mbar)
D4 ^a	Ground shock (1-ton row)	$\perp^b$	775	0.140	722	11.9
			2,168	0.097	2020	8.25
			1,060	0.097	988	8.24
			560	0.106 ^c	522	9.04
			3,800	0.0049	3540	0.417
			11,750	0.00196	10950	0.167
	Gas vent (1-ton row)	$\perp^b$	775	0.123 ^d	722	10.5
			2,168	0.0616 ^d	2020	5.25
			1,060	—	988	— ^e
			560	0.114 ^c	522	9.7
			3,800	0.0115 ^c	3540	0.98
			11,750	0.00429	10950	0.365
	Ground shock (2-ton row)	$\perp^b$	775	0.123 ^d	587	10.5
			2,168	0.0616 ^d	1643	5.25
			1,060	0.139	803	11.8
	Gas vent (2-ton row)	$\perp^b$	775	0.169	587	14.4
			2,168	0.131	1643	11.2
			1,060	0.336 ^e	803 ^e	28.6 ^e
	Unidentified 3rd peak ^f		560	0.143 ^c	—	—
			3,800	0.0088	—	—
			11,750	0.00361	—	—
	4th peak ^f		560	0.060 ^c	—	—
			3,800	0.0085 ^c	—	—
			11,750	0.00315	—	—
	5th peak ^f		560	0.124 ^c	—	—
			3,800	0.0187	—	—
			11,750	0.00795	—	—
	6th peak ^f		560	0.115 ^c	—	—
			3,800	0.0232 ^c	—	—
			11,750	0.0101	—	—

^aThe D4 detonation was a double row of charges, emplaced along the contour of a gentle slope. The downhill row (1-ton row) consisted of 18 charges, each of 1-ton yield. The uphill row (2-ton row) consisted of 14 charges, 12 of 2-ton and 2 of 1-ton yield. The spacing between rows was 46 ft (approximately 41 ft/ton^{1/3}). The 1-ton row was detonated approximately 150 msec before the 2-ton row.

Mean yield of 1-ton row = 1.0 ton
 Total yield of 1-ton row = 18.0 tons
 Mean DOB^g of 1-ton row = 19.7 ft/ton^{1/3}
 Mean spacing of charges in 1-ton row = 35 ft/ton^{1/3}
 Mean yield of 2-ton row = 1.86 ton
 Total yield of 2-ton row = 26.0 tons
 Mean DOB^g of 2-ton row = 17.9 ft/ton^{1/3}
 Mean spacing of 2-ton row = 28.5 ft/ton^{1/3}

^bPerpendicular overpressures include values measured along both perpendiculars (closer to the 1-ton row, and closer to the 2-ton row). The measured values at a given range along these two directions differ by about 30% in some cases, due to partial and variable overlap between pulses contributed by the two rows. The various contributions are usually inseparable and precise reinforcement factors cannot be determined.

^cAdjusted values—overpressure or pulse identification may be uncertain.

^dGas-vent pulse for 1-ton row overlaps ground-shock pulse for 2-ton row in this direction.

^eGas-vent pulses for both rows coincide at this station; scaled values are scaled on the basis of "2-ton row" alone.

^fThe waveforms of the pulses observed off the end of the rows were complex, consisting of multiple peaks whose relative amplitudes and attenuation rates varied significantly. Six distinct peaks were observed; the third, fourth, fifth, and sixth peaks could not be assigned to any specific source, due to the great length and the time delay of the two rows with resultant overlap and variable reinforcement between various pulses. The fifth and sixth peaks were apparently dominant at all ranges off the end of the rows. No scaled distances or reinforcement factors could be determined due to the fact that the sources of the dominant pulses are not always identifiable.

^gAll depths are measured to the center of the charges. The charges in the 1-ton row were emplaced in underreamed holes, and had a height-to-diameter ratio of about 1.0. The holes for the 2-ton row were not underreamed, and the charges had a height-to-diameter ratio of about 4 to 1. These charges were approximately 10 ft long. Thus, the upper portions of the 2-ton charges were quite close to the ground surface, and these charges probably vented at rather early time (causing high gas-vent overpressures from the 2-ton row).

medium, and explosive type (for single-charge detonations). Close and intermediate range peak overpressures for most cratering experiments attenuate with distance approximately as $R_s^{-1.2}$. The largest transmission factor observed for a given experiment will thus provide an indication of the maximum expected damage-producing airblast from any experiment at the same scaled burial depth with the same explosive in the same medium.

Calculated transmission factors for all buried Trinidad experiments are listed in the last column of Tables D1 through D4. These values will be used to compare the various experiments.

SINGLE-CHARGE BURIED EVENTS

The most consistent airblast results are generally obtained from single-charge events. Therefore, it is of interest to examine Detonations B1 through B8. The three ammonium nitrate fuel oil (ANFO) events, B1, B2, and B3, show considerable scatter. Values of f_{gs} are comparable to the other single-charge events, although B2 and B3 appear rather low. Values of f_{gv} for B1 and B3 are higher than for any of the other (aluminized slurry) experiments, but those for B2 are lower. B2 was intermediate between B1 and B3 in scaled depth. The erratic behavior of the gas-vent airblast from ANFO detonations is believed to be a result of erratic vent times that are not closely correlated with scaled depth of burial.¹⁶

The aluminized ammonium-nitrate slurry events show more consistent behavior. Values of f for ground-shock

(f_{gs}) and gas-vent (f_{gv}) are plotted as a function of scaled depth of burial in Fig. D1. In this case, f_{gs} decreases slowly with increasing scaled depth of burial, as expected. A straight line is fitted through the maximum values of f_{gs} , which are approximately twice those observed for TNT experiments at comparable scaled depths. Values of f_{gv} show more deviation, indicating that some scatter of the vent times occurs for these experiments as well. However, f_{gv} does decrease sharply with increasing depth, as it should. The plotted values of f_{gv} are greater than those observed for TNT events at comparable scaled depths by a factor of two to ten. Two curves are drawn through the maximum values of f_{gv} ; the lower curve is considered the best estimate of the maximum gas-vent transmission factors for typical events.

ROW-CHARGE EVENTS

Airblast from a row of equal-size charges at a given scaled depth is greater than the airblast that would be produced by only one of the charges detonated at the same scaled depth. The reinforcement of airblast for row-charge events is usually measured by the ratio of the peak overpressure (or value of f), at a given distance from the row, to the peak overpressure (or value of f) at the same distance from a single charge of the same weight as the average weight of the charges in the row and at the same average scaled depth of burial. This ratio is known as the "difference factor" between row and single charge airblast.

The difference factors for past experiments under partially controlled

Fig. D1. Observed single-charge transmission factors as a function of scaled depth of burst for aluminized ammonium nitrate slurry detonations, Project Trinidad.

conditions have been found to fit a law of the form:

$$\text{Difference factor} = n^B$$

where n = number of charges in the row
and B = an exponent whose value depends upon the following:

- The azimuth, relative to the alignment of the row, at which the airblast is observed. "B" will be a maximum for observations perpendicular to the row, and will decrease at azimuths closer to the row axis.

- The scaled depth of burial.
- The scaled spacing between charges.
- The rock type
- The type of explosive
- The average charge weight
- The absolute length of the row
- The scaled range at which the airblast is observed.

Difference factors and values of B have been calculated for the Trinidad row experiments. First, the average charge weight and the average scaled depth of burial for each row were determined (Table D1). The observed overpressures

Table D5a. Ground-shock-induced overpressure reinforcement correction factors for Trinidad row-charge detonations.

$$\Delta P(\text{row charge}) = n^B \Delta P(\text{single charge at same scaled range})$$

Detonation	Direction	n	Difference factor, n^B	B
C1	Perpendicular to row	5	2.44	0.554
	Parallel to row		1.60	0.292
C2	Perpendicular to row	5	3.31	0.744
	Parallel to row		1.23	0.128
C3	Perpendicular to row	7	3.08	0.578
	Parallel to row		2.30, 1.51 ^a	0.428, 0.212 ^a
C4 (delay = 0.05 sec)	Perpendicular to row	5	(0.622) ^b	<0
	Parallel to starting end		(0.727)	<0
	Parallel to final end		(0.781)	<0
C5 (delay = 0.025 sec)	Perpendicular to row	5	(0.850) ^b	<0
	Parallel to starting end		1.13	0.076
	Parallel to final end		2.29	0.515
C6	Perpendicular to row	10 ^c	4.90	0.690
	Parallel to row		3.21	0.506
D1	Perpendicular to row, uphill	9	8.42	0.97
	Perpendicular to row, downhill		6.83	0.874
	Parallel to row		2.46	0.41
D2	Perpendicular to row	5	4.55	0.940
	Parallel to row		3.56	0.789
D3	Perpendicular to 1-ton row	6	4.07	0.784
	Parallel to 1-ton row	of 1 ton	1.13	0.068
	Perpendicular to 2-ton row	6	—	—
	Parallel to 2-ton row	of 2 tons	2.42	0.493

^aTwo values given because signal showed double peak; larger value listed first.

^bValues in parentheses indicate airblast overpressures less than comparable fitted single-charge values; considered somewhat questionable.

^cTwo parallel 5-charge rows; data reduced as airblast from single 10-charge row.

and distances were then scaled according to the average charge weight, and values of f were calculated. The largest observed value of f in each direction for each experiment was compared to the value of f for a single-charge experiment at the same scaled depth of burial (see Fig. D1), and the difference factor was calculated: difference factor = f row-charge / f single charge for the same scaled depth. The ground-shock line in

Fig. D1 was used to obtain the value of f_{gs} for a single charge, and the lower of the two curves through the gas-vent values was used to obtain f_{gv} for a single charge. The calculated difference factors are listed in Table D5a (ground-shock observations) and Table D5b (gas vent observations).

Because the number of charges for each experiment is known, the value of B can be calculated. The B -values are

Table D5b. Gas-vent-induced overpressure reinforcement correction factors for Trinidad row-charge detonations.

$$\Delta P(\text{row charge}) = n^B \Delta P(\text{single charge at same scaled range})$$

Detonation	Direction	n	Difference factor, n^B	B
C1	Perpendicular to row	5	1.63	0.304
	Parallel to row		1.19	0.108
C2	Perpendicular to row	5	1.80	0.365
	Parallel to row		(1.0) ^a	(0)
C3	Perpendicular to row	7	3.50	0.644
	Parallel to row		2.16, 2.44 ^b	0.396, 0.459 ^b
C4 (delay = 0.05 sec)	Perpendicular to row	5	2.03	0.44 ^c
	Parallel to starting end		2.37	0.536
	Parallel to final end		2.33	0.526
C5 (delay = 0.025 sec)	Perpendicular to row	5	1.36	0.191
	Parallel to starting end		1.50, 1.21 ^d	0.252, 0.117 ^d
	Parallel to final end		1.95	0.415
C6	Perpendicular to row	10 ^e	9.26, 5.42 ^d	0.966, 0.734 ^d
	Parallel to row		5.66, 4.42	0.753, 0.645
D1	Perpendicular to row, uphill	9	(1.0)	(0)
	Perpendicular to row, downhill		(0.505)	<0
	Parallel to row		1.26	0.105
D2	Perpendicular to row	5	3.67	0.808
	Parallel to row		(0.88)	<0
D3	Perpendicular to 1-ton row	6	3.05	0.622
	Parallel to 1-ton row	of 1 ton	1.73	0.306
	Perpendicular to 2-ton row	6	2.92	0.598
	Parallel to 2-ton row	of 2 tons	1.62	0.269

^aValues in parentheses indicate airblast overpressures less than comparable fitted single-charge values; considered somewhat questionable.

^bLarger of two listed values derives from questionable airblast measurement.

^cQuestionable because of the very rapid attenuation of gas-vent overpressures with distance perpendicular to the C4 row.

^dTwo values given because signal showed double peak; larger value listed first.

^eTwo parallel 5-charge rows; data reduced as airblast from single 10-charge row.

listed in the last column of Tables D5a and D5b.

Experiment D3 consisted of two six-charge rows, but the separation and time delay between the rows were sufficiently great that almost no airblast interaction or reinforcement occurred; therefore, the pulses from each row were treated as if they originated from two separate six-charge rows and were analyzed separately. The C6 double row, on the other hand, had no interrow delay. Separate signals from the two rows could not be identified, and the event was treated as a single ten-charge row (rather than two five-charge rows).

It should be noted that, except for D1, all rows consisted of aluminized ammonium-nitrate slurry charges in rock very similar to that of the B-series tests. Therefore, the comparison of single-charge values of f from Fig. D1 to f values for the row-charge events should be valid. Experiment D1 used ANFO and may show the erratic gas venting behavior noted for the single charge ANFO experiments. The value of f_{gv} for D-1 did indeed turn out to be very low (Table D5b), being comparable to that expected for a single-charge ($B \approx 0$).

The B-values in Tables D5a and D5b show an enormous amount of scatter, varying all the way from $B = 0$ (single-charge airblast) to $B \approx 1.0$ (perfect acoustic reinforcement). The average values tend to be somewhat greater (more reinforcement) than those previously determined for relatively large-yield rows (charge weights ≈ 10 tons), but less than the observed reinforcement for small-yield rows (charge weights ≈ 64 lb).²² No definite correlation could be established

with scaled depth of burial, number of charges in the row, or scaled spacing between charges.²² The reasons for this erratic behavior are not fully understood, but are believed to be related to the inhomogeneous nature of the medium, relatively small charge weights, and irregular venting behavior. Many of the experiments showed highly complex waveforms in which some peaks could not be positively identified or interpreted. Irregular and unexplained variations in vent times between the individual charges in a row may have contributed to the scatter in the data. The ground-shock-induced pulses showed complex multiple peaks for some experiments. It is impossible to establish completely consistent relationships between single- and row-charge airblast similar to those found for experiments in more uniform media. However, best estimates of the row-charge difference factors are given in Table D6. The conclusions discussed below must be considered tentative at best. A more extensive discussion of the observed overpressures and attenuation rates for individual row-charge events is given in Ref. 16.

Waveforms observed off-the-end-of and perpendicular to the D4 (RR1) double row were of extraordinary complexity. The length of the rows and the interrow delay, as well as the inconsistent venting behavior from charge to charge within a row, caused various pulses to overlap and reinforce in a complex manner dependent on azimuth and range. Overlap rendered the source of some peaks unidentifiable, particularly off the end of the rows. For these reasons, scaling of the overpressures and determination of

Table D6. Airblast amplitudes for row-charges expressed in terms of single-charge airblast amplitudes.

Conditions	Ground-shock-induced overpressures	Gas-vent-induced overpressures
Simultaneous row-charge		
Perpendicular	$\Delta P_r = n^{0.75} \Delta P_s$	$\Delta P_r = n^{0.6} \Delta P_s$
Off-the-end	$\Delta P_r = n^{0.5} \Delta P_s$	$\Delta P_r = n^{0.45} \Delta P_s$
Delayed (intercharge) row-charges		
Perpendicular: delay $\Delta T = 0.25 \text{ sec/ton}^{1/3}$	$\Delta P_r \cong \Delta P_s$	$\Delta P_r^a \cong n^{0.45 \text{ to } 0.55} \Delta P_s$
Off-the-starting end	$\Delta P_r = \Delta P_s$	$\Delta P_r \cong n^{0.45} \Delta P_s$
Off-the-finish end $\Delta T = 0.025 \text{ sec/ton}^{1/3}$	$\Delta P_r = n^{0.5} \Delta P_s$	
$\Delta T = 0.050 \text{ sec/ton}^{1/3}$	$\Delta P_r \cong \Delta P_s$	

^a Estimate based on very limited data.

the reinforcement factors cannot be accurately accomplished. It is hoped that this situation will improve when more data from long rows become available. Meanwhile, the D4 data cannot be included in the "reinforcement factor" analysis, and we can only predict approximate "maximum" expected reinforcement factors for very long or complex rows based on the particular case in question.

Other problems with the D4 measurements include inconsistent attenuation rates in a given direction (related to the problems mentioned above), and some questionable data points as noted in the table.¹⁶

The principal characteristic of the airblast data for row-charges is the large amount of scatter. However, the observed difference factors (i.e., airblast reinforcement) for all experiments in this series have a fairly well-defined upper bound for each component of the airblast pulse (gas vent and ground shock). These estimated upper limits, as listed in Table D6, may be used to predict reliably the airblast amplitudes for similar experi-

ments. Estimates of the difference factors presented in Table D6 should apply most accurately for detonations similar to those at Trinidad; i.e., five to ten charge rows, charge weights from 0.5 to 2 tons, near-optimum intercharge spacing (16 to 35 ft/ton^{1/3}), and aluminized ammonium-nitrate slurry explosive in weak rock. These difference factors apply either to the peak single-charge overpressures ΔP_s at intermediate ranges, or to the maximum single-charge values of f.

For single row-charges, Table D6 relates overpressures generated by the row-charge (ΔP_r) to those generated by a single charge (ΔP_s) weighing the same as the average charge in the row and at the same scaled depth of burial. The number of charges in the row is n.

For simultaneous double row-charges near optimum interrow spacing, the overpressures and difference factors were approximately the same as for a single row containing the same number of charges as both double rows; i.e., n is the total number of charges in both rows.

The single-charge transmission factors (Fig. D1) and row-charge

difference factors discussed in this chapter may be used as an approximate

means of predicting airblast from future events of a similar nature.²²

Appendix E

Laboratory Testing of Fallback Material

J. M. Duncan* and C. K. Chan†

A program of laboratory tests was conducted at the Rockfill Test Facility at the University of California** to measure the physical properties of the fallback in the D4 crater.

The tests described were performed for two purposes. The primary objective was to obtain information that could be used to estimate the amount of time-dependent settlement of the fallback, and the amount of settlement that would result from saturation of the fallback by surface water or groundwater. A second objective of the test program was to provide information concerning other physical properties of the fallback, such as grain-size distribution, relative density, and shear strength characteristics, that would add to the available information concerning the engineering characteristics of fallback materials in general.

The rocks, which are composed of quartz, plagioclase and orthoclase feldspars, clay, and minor amounts of ferromagnesian minerals, are soft and poorly cemented. Although they do not slake when placed in water, they are softened by water and many sandstone fragments could be broken easily by hand after soaking in water. The average in situ dry density of the rock before the blast was 150.8 lb/ft^3 . As described in Chapter 6, the mass density of 128.8 lb/ft^3

was determined by excavating 107.2 yd^3 from a trench and weighing the material. The grain-size was measured using the point-count technique.¹⁷ The fallback contained a few rocks as large as 4 or 5 ft, but about 99% of the particles were smaller than 15 in. The smallest particles were finer than the No. 200 sieve.

Thirty-four tons of the excavated fallback material were trucked to the Rockfill Test Facility for testing. Samples were taken from the material to determine its water content. The entire 34 tons were sieved to determine the grain-size distribution and to separate the material into a number of size fractions, the smallest consisting of material passing the No. 200 sieve. The size fractions were subsequently recombined to form "model" materials with grain-size distribution curves parallel to the field curve, but with smaller maximum particle sizes. Tests were conducted on these model materials to determine maximum and minimum densities for relative density determinations, and triaxial and one-dimensional compression tests were performed to determine the stress-strain and strength characteristics. Tests were conducted on specimens compacted to the in situ relative density and to looser densities.

WATER CONTENT AND IN SITU DRY DENSITY

Samples from the material received for testing at the Rockfill Test Facility were found to have an average water content of 4.8%, which is about the same value as determined from core samples of the rocks before the blast. Using a water

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**The Rockfill Test Facility, located at the Richmond Field Station, is operated by the University of California for the California Department of Water Resources.

content of 4.8% and the moist unit weight determined by trenching in the fallback ($\gamma_{in} = 128.8 \text{ lb/ft}^3$) the in situ dry unit weight (γ_d) was calculated to be 123.0 lb/ft^3 .

GRAIN SIZE DISTRIBUTION, PARTICLE COMPOSITION, AND SPECIFIC GRAVITY

The grain-size distribution curve determined by sieving the fallback material received at the Rockfill Test Facility is shown in Fig. E1, together with curves determined by the point-count technique at the east and the west ends of the crater. The curve determined by sieving lies between the other two curves for the range of sizes larger than about 0.2 in., but shows larger percentages of the finer sizes. It is seen that 23% of the fallback is finer than the No. 4 sieve, and about 2% is finer than the No. 200 sieve.

The grain-size distribution curves for the "model" materials are shown in Fig. E2. These curves are parallel to the grain-size curve of the material received for testing, and were selected so that the largest size particles used in each type of test were about one-sixth as large as the minimum dimension of the test specimen.

The material was examined after sieving to determine the compositions and specific gravities of the various size fractions, as shown in Table E1. The shale and siltstone were softer than the sandstone and were therefore broken into smaller particles by the blast. As a result, the smaller particles tend to be somewhat softer than the larger ones. The same would probably be true of any fallback containing rocks with varying hardness. The specific gravities determined for the various size fractions

Fig. E1. Comparison of grain-size distribution curves determined by point count technique and by sieving.

Fig. E2. Grain-size distribution curves for material as received and for test specimens.

Table E1. Composition and specific gravities of various sized fractions of Trinidad fallback.

Size fraction (in.)	Percent sandstone	Percent shale and siltstone	Specific gravity
6 to 3	91	9	2.60
3 to 1-1/2	98	2	—
1-1/2 to 3/4	84	16	2.64
3/4 to 3/8	67	33	—
3/8 to No. 4	—	—	2.66
No. 4 to No. 8	50	50	—
All material finer than No. 4	—	—	2.60

varied from 2.60 to 2.66, with an average value of 2.63.

RELATIVE DENSITY

Tests were performed to determine the maximum and minimum densities for

four "model" materials having grain-size distribution curves parallel to that for the field material, but smaller maximum particle sizes. Tests were performed on materials with maximum particles sizes equal to 2 in., 1 in., 1/2 in., and the No. 4 sieve size. The results of these tests

are shown in Fig. E3. The maximum and minimum densities increase with increasing maximum particle size. Extrapolating the experimental curves to a maximum particle size of 15 in., it was estimated that the maximum density of the material with the field gradation would be about 130.0 lb/ft³, and the minimum about 109.5 lb/ft³. Using these values of maximum and minimum density, it was determined that the relative density of the fallback in the field was about 70%.

This relative density of the fallback in the field is somewhat higher than was anticipated. However, studies by Walker and Whitaker²¹ and Silver and Seed²³ have shown that uniform sands can be compacted efficiently by "pluvial compaction," or dropping into place. Silver and Seed found that a uniform, angular silica sand that they tested could be

compacted to as high as 95% relative density by pluvial compaction. To the writers' knowledge, no studies have been performed to determine the effectiveness of pluvial compaction for well-graded materials like the Trinidad fallback.

TRIAXIAL TESTING

Most of the triaxial and one-dimensional compression test specimens were formed at relative densities close to those determined for the fallback in the field, in order that the results of the tests could be used to evaluate the properties of the material at its *in situ* density. A few tests on smaller size specimens were performed at looser densities to investigate the effects of changes in density on the strength, compressibility, and compression due to wetting.

Fig. E3. Variations of maximum and minimum density with maximum particle size.

Four drained triaxial tests were performed on 36-in. diameter specimens containing particles as large as 6 in. The grain-size distribution curves for the material tested are shown in Fig. E2. The specimens were compacted to dry densities ranging from 119.6 lb/ft^3 to 120.6 lb/ft^3 , which corresponds to relative densities of $71 \pm 2\%$, very close to the field value.

Two tests were conducted on material that was compacted and tested at water contents of 5%, essentially the same as the field value. The second two specimens were saturated after compaction by circulating water through them and by applying back pressure. The permeability of the material was quite low, and considerable time was required to saturate the specimens. After the tests the wet specimens did not drain; they had considerable cohesion and were able to stand unsupported, as shown in Fig. E4.

The stress-strain and volume change curves for the two tests performed using $\sigma_3 = 15 \text{ psi}$ are shown in Fig. E5, and those for tests conducted with $\sigma_3 = 30 \text{ psi}$ are shown in Fig. E6. The stress-strain curves shown in Figs. E5 and E6 and in other figures in this report have not been corrected for the loads carried by the rubber membranes used to confine the specimens. The loads are not very large, however, and applying the appropriate correction to the axial stress results in a reduction in the maximum principal stress ratio of the order of 0.1, or about 2%. Although the values of principal stress ratio shown on the stress-strain curves have not been corrected, the stresses at failure have been corrected for the purpose of calculating the angles

Fig. E4. Wet specimen (36-in. diameter) after testing.

of internal friction, which are discussed in a subsequent section.

It may be noted that the wet specimens were considerably weaker than the dry ones. The stress-strain curves for the wet specimens are flatter than for the dry ones tested at the same pressure, and the peak values of principal stress ratio are smaller. It may also be seen

Fig. E5. Stress-strain and volume change curves for specimens compacted to 71% relative density (confining pressure, 15 psi).

Fig. E6. Stress-strain and volume change curves for specimens compacted to 71% relative density (confining pressure, 30 psi).

that the wet specimens compressed more during shear than the dry ones. The material is quite compressible; even at the low confining pressures employed in the tests, the volumes of all the specimens decreased during shear.

Four drained triaxial tests were conducted on 6-in. diameter specimens. As was the case in the tests on 36-in. diameter specimens, two specimens were tested wet and two were tested dry, using confining pressure of 15 and 30 psi. The maximum particle size in the 6-in. diameter specimens was 1-in. The specimens were prepared at densities of 114.1 to 114.8 lb/ft³, correspond to relative densities of $77 \pm 1\%$.

The stress-strain curves for the tests are shown in Figs. E7 and E8. As in the case of the 36-in. diameter specimens,

Fig. E7. Stress-strain and volume change curves for specimens compacted to 77% relative density (confining pressure, 15 psi).

Fig. E8. Stress-strain and volume change curves for specimens compacted to 77% relative density (confining pressure, 30 psi).

the specimens tested wet were considerably weaker than the dry ones, and compressed more during shear.

Eight drained triaxial tests were conducted on 2.8-in. diameter specimens, with materials having a maximum particle size of 0.47 in. Two of these tests were conducted on wet specimens that were compacted to dry densities of 108.8 lb/ft³ and 109.3 lb/ft³, corresponding to relative densities of 71% and 73%. The stress-strain curves for these tests are shown in Figs. E9 and E10, together with stress-strain curves for dry material at the same relative density estimated from the results of tests on dry specimens at higher and lower densities.

The remaining six tests on 2.8-in. diameter specimens were conducted on dry specimens with relative densities

Fig. E9. Stress-strain and volume change curves for specimens compacted to 73% relative density (confining pressure, 15 psi).

Fig. E10. Stress-strain and volume change curves for specimens compacted to 73% relative density (confining pressure, 30 psi).

ranging from 54.5% to 80.5%. The stress-strain and volume change curves for these tests are shown in Figs. E11 and E12.

ONE-DIMENSIONAL COMPRESSION TESTS

Eight one-dimensional compression tests were conducted on material having a gradation curve parallel to the field gradation curve and a maximum particle size equal to the No. 4 sieve. The tests were conducted on specimens confined in 4-in. diameter, 1-in. high Teflon-lined consolidation rings. Two series of tests were performed, one on specimens compacted to 80% relative density, and the other on specimens compacted to 50% relative density.

The compression-time curves for one of these tests is shown in Fig. E13. The specimen was compacted dry-to-80% relative density and was then subjected to a pressure of 10 psi. Application of this pressure resulted in an immediate axial compression of about 0.8%, followed by a small amount of time-delayed compression. Similarly, increasing the pressure to 20 psi and then to 30 psi resulted in further immediate compression followed by creep at a slow rate.

As shown in Fig. E13, adding water to the specimen while the pressure was maintained at 30 psi caused a large increase in the settlement rate. Over a period of 100 min. after the water was added, the settlement increased from about 2.8 to about 9.4%.

The results for all four one-dimensional compression tests performed on specimens compacted to 80% relative density are shown in Fig. E14. These four specimens were wetted while

Fig. E11. Stress-strain and volume change curves for specimens compacted to three relative densities (confining pressure, 15 psi).

Fig. E12. Stress-strain and volume change curves for specimens compacted to three relative densities (confining pressure, 30 psi).

Fig. E13. Compression time curves for specimens compacted to 80% relative density.

Fig. E14. One-dimensional compression curves for specimens compacted to 80% relative density.

subjected to pressures of 30, 20, 10, and 0.1 psi. The specimen which was wetted at 0.1 psi swelled about 2.6% when the water was added, but all the others compressed upon wetting. Similar results for specimens compacted to 50% relative density are shown in Fig. E15. As would be expected, the amount of swell induced by wetting at the lowest pressure was smaller, and the amounts of compression due to wetting at higher pressures were larger for these looser specimens.

As for other soils tested previously, the amounts of compression induced by wetting the specimens after loading were approximately equal to the difference in the amounts of compression for wet and dry specimens at the same pressure. Thus the amount of compression due to wetting at any pressure can be estimated with compression curves for wet and dry specimens.

PARTICLE BREAKAGE

Several specimens were sieved to determine the amount of particle breakage during testing. The results are shown in Table 2 in terms of the particle breakage factor B, defined by Marsal.²⁴ This factor is the sum of the differences (of the same sign) in the percentages retained on each sieve before and after a test. Larger values of B indicate more change in gradation and more particle breakage during the test. The data in Table E2 indicate that the particle breakage was

Table E2. Values of particle breakage factor B determined by relieving triaxial specimens after testing.

Confining pressure (psi)	Specimen diameter					
	36 in.		6 in.		2.8 in.	
	Dry (%)	Wet (%)	Dry (%)	Wet (%)	Dry (%)	Wet (%)
15	6	18	11	26	10	21
30	6	15	10	23	9	17

Fig. E15. One-dimensional compression curves for specimens compacted to 50% relative density.

greater for the wet than for the dry specimens. It may also be noted that there was more breakage for the smaller specimens that contained smaller, softer particles.

SUMMARY OF LABORATORY TEST PROGRAM

The relative density of the fallback in the field is perhaps the most important factor controlling its shear strength, compressibility, compression upon wetting, and susceptibility to settlements or liquefaction during earthquakes. Materials with relative densities as high as that determined for the Trinidad fallback (70%) are nearly as dense as well-engineered fills and should thus not be susceptible to severe problems of settlement and stability.

In order to determine the relative density of the fallback in the field, it was necessary to extrapolate on the basis of minimum and maximum density values determined for model materials with smaller maximum particle sizes. Because of the importance of knowing the relative densities accurately, it would be desirable to study the effectiveness of pluvial compaction for well-graded fallback materials. If enough data could be obtained for various types of materials, it might be feasible to predict the relative density based on small-scale laboratory and/or field tests conducted before the crater was made.

The results of all the triaxial tests performed are summarized in Table E3, and the measured values of ϕ are plotted against the relative densities of the test specimens in Fig. E16. All of the values shown in Fig. E16 are for tests conducted

with $\sigma_3 = 15$ psi; as shown in Table E3, the values of ϕ are about 1 to 2 deg lower for tests conducted with $\sigma_3 = 30$ psi.

It may be seen that the angles of internal friction are about 6 deg lower on the average for wet specimens than for dry ones. The values of ϕ measured for all three specimen sizes are in fairly good agreement, indicating that it would be possible to determine the angle of internal friction with reasonable accuracy by testing "model" materials, even though the particles in the various size ranges vary in hardness.

For the in situ relative density of 70%, the angle of internal friction for the material in a dry condition is about 43 deg, and for the material in a wet condition, about 36.5 deg. These values correspond to $\sigma_3 = 15$ psi as in Fig. E16; the values of ϕ for both wet and dry conditions would be somewhat smaller for higher confining pressures.

The values of volumetric strain due to wetting measured in the triaxial and one-dimensional compression tests are shown in Fig. E17, plotted against the maximum particle sizes. It may be seen that the specimens composed of smaller sizes underwent much more compression due to wetting than did those containing larger particles. By extrapolating the curves to the maximum particle size in the field (about 15 in.), it is possible to estimate the amount of settlement which would be induced by wetting. As may be seen for the data obtained in one-dimensional compression tests on specimens composed of material with No. 4 maximum particle size, the compression induced by wetting under at-rest pressure conditions is about 20% greater than

Table E3. Summary of triaxial test results.

Test	Maximum particle size (in.)	Confining pressure, σ_3 (psi)	Density, γ_d (lb/ft ³)	Relative density, D_r (%)	Principal stress ratio, $\left(\frac{\sigma_1}{\sigma_3}\right)_f$	Angle of internal friction, ϕ (deg)
36-in. Dry	6	15	120.3	71.5	5.32	43.1
36-in. Dry	6	30	120.3	71.5	4.95	41.5
36-in. Wet	6	15	120.6	73.0	3.82	35.8
36-in. Wet	6	30	119.6	69.0	3.58	34.3
6-in. Dry	1	15	114.1	76.0	5.92	45.3
6-in. Dry	1	30	114.3	76.0	5.44	43.6
6-in. Wet	1	15	114.8	78.0	4.08	37.3
6-in. Wet	1	30	114.5	77.0	3.98	36.7
2.8-in. Dry	0.47	15	111.3	80.5	5.23	42.8
2.8-in. Dry	0.47	30	111.0	79.5	4.93	41.5
2.8-in. Dry	0.47	15	106.8	63.5	4.76	40.8
2.8-in. Dry	0.47	30	106.1	61.0	4.81	40.0
2.8-in. Dry	0.47	15	105.0	56.5	4.87	41.2
2.8-in. Dry	0.47	30	104.5	54.5	4.65	40.2
2.8-in. Wet	0.47	15	108.8	71.0	4.21	38.0
2.8-in. Wet	0.47	30	109.3	73.0	3.65	34.7

the volumetric strain induced by wetting in triaxial tests with the specimens confined under equal all-around pressures.

Using the extrapolated curves shown in Fig. E17 and allowing for about 20% higher volumetric strains under at-rest pressure conditions, it is estimated that the compression due to wetting would amount to about 0.9% with overburden pressure (σ_1) equal to 15 psi, and about 1.5% with overburden pressure equal to 30 psi. These values are plotted in Fig. E18, which shows the relationship between the overburden pressure and the percent compression due to wetting under at-rest pressure conditions.

With this curve, calculations have been made to determine the settlements to be expected in fallback layers of various thicknesses if the groundwater rose to within 5 ft of the ground surface. The results of these calculations are shown in Table E4. It may be seen that the expected settlements due to groundwater rise exceed one-tenth of a foot for layers more than 20 ft thick, and that they are more than 0.2 ft for layers thicker than about 30 ft. The results would be somewhat different if the groundwater rose to some level other than 5 ft beneath the surface, but the settlements due to wetting could be estimated using the same procedures.

Fig. E16. Variations of angle of internal friction with relative density.

Fig. E17. Variation of volumetric strain due to wetting with maximum particle size.

Fig. E18. Variation of compression due to wetting with overburden pressure for at-rest pressure conditions.

A small amount of creep settlement of the fallback would be expected even if the groundwater did not rise. The curves shown in Fig. E13 indicate that the compression of the dry fallback continues to increase approximately linearly with the logarithm of time. The time curves shown in Fig. E13 indicate that the settlement rate is independent of pressure, and amounts to about 0.1% per log cycle of time. Thus the creep settlement of a 10-ft thick layer would be expected to amount to about 0.01 ft in the period from 3 to 30 days, an additional 0.01 ft in the period from 30 days to about 1 yr, another 0.01 ft in the period from 1 to 10 yr, and so on. These creep settlement rates are quite small and are not considered to be significant.

Settlement of the fallback would also be caused by increased static pressures

Table E4. Surface settlement due to groundwater rise within 5 ft of ground surface for various fallback layer thicknesses.

Layer thickness, T (ft)	Height of ground-water rise, H (ft)	Initial effective overburden pressure, P_0' (psi)	$\left(\frac{\Delta H}{H}\right)$ (%)	Settlement, ΔH (ft)
5	0	0	0.00	0.00
10	5	6.25	0.40	0.02
15	10	8.32	0.52	0.05
20	15	10.4	0.64	0.10
25	20	12.5	0.76	0.15
30	25	14.6	0.87	0.22

Note:

Effects of rebound due to buoyancy are neglected.

from fills placed on the fallback or from slowly moving trains. The magnitudes of these settlements could be estimated using the compression curves shown in Fig. E14 for wet or dry material, whichever is appropriate.

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13. ABSTRACT A series of single-, row-, and multiple-charge cratering detonations, with individual charge weights of one to two tons, were carried out in weak, interbedded sandstones and shales near Trinidad, Colorado, in 1970 and 1971. The principal objectives of these excavation experiments were: to obtain single-charge cratering curves; to verify row-charge designs for achieving a specified excavation; to determine the effects of millisecond delays in row-charge cratering; to experiment with cratering in varying terrain; and to compare the cratering effectiveness of several explosives. Three varieties of aluminized ammonium-nitrate blasting agents and ANFO were used. Airblast and seismic effects of each detonation were monitored. The series culminated with the excavation of a 400-foot long railway cut with 44 tons of explosives distributed among 32 charges.		

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