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RESEARCH REPORTS

22/SC-4483 (RR)

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NUCLEAR EXPLOSIONS--

PEACEFUL APPLICATIONS

PROJECT

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HIGH-EXPLOSIVE DITCHING
FROM LINEAR CHARGES
FINAL REPORT, JULY 1961

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Technical Services, Department of Commerce,
Washington 25, D. C.

SC-4483(RR)
TID 4500 (16th Ed.)
NUCLEAR EXPLOSIONS--
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HIGH-EXPLOSIVE DITCHING FROM LINEAR CHARGES

R. H. Carlson, 5112

July 1961

ABSTRACT

Weights of linear high-explosive charges fired on the Yucca Lake playa of the Nevada Test Site varied from 0.23 to 42.7 pounds per foot. Crater and ditch dimensions and volumes resulting from these shots, fired during the fall of 1959 and spring of 1960, are presented here as a function of charge burst depths. Scaling relationships determined are as expected; i. e., square-root scaling of linear-charge weight per foot for ditch width and depth and a direct linear-charge weight relationship to ditch volume are obtained. Permanent ground surface displacement varies as the -3.22 power of the scaled distance from the charge. Detonation effects, charge shape effects, ditch erosion, and ditch cross sections are discussed. The appendixes present Toboggan data, results of soils investigation, and mathematical treatment given the data.

ACKNOWLEDGMENTS

Acknowledgments are due the following Sandia Field Test personnel who have made major contributions to Project Toboggan: H. R. MacDougall, Test Group Director; B. S. Snow, Experiment Coordinator; F. Shoemaker and W. R. Drake, Arming and Firing; and W. G. Foy and H. E. Lockwood, Photography.

Sandia research personnel responsible for data reduction were J. R. Wetherholt and D. B. Hayes. R. B. Allison obtained all data on the shatter wedge specimens.

The following Holmes and Narver personnel also made major contributions to this project: C. W. Embree, data drawings, and J. A. Bobo and H. C. Brock, topographical survey.

Statistical calculations and analyses (Appendix C) were done by D. B. Owen and the staff of the Statistical Research Division at Sandia.

Support of the Office of Test Operations of the Albuquerque Operations Office and of the San Francisco Operations Office of the AEC is greatly appreciated.

NOTE: Illustrations in this report are reproduced from the best copy available.

FOREWORD

Project Toboggan was planned and accomplished by Sandia Corporation at the request of Lawrence Radiation Laboratory which has technical responsibility for the Plowshare program. This final report, which includes all test data obtained during Phase I and Phase II of Project Toboggan, supersedes, with one exception (Appendix A), the interim report (Carlson, R. H., High-Explosive Ditching from Linear Charges, Interim Report, Project Toboggan, Phase I, SC-4441(RR), May 1960). However, correlations and conclusions presented in that report are still valid.

Operational aspects of Toboggan are included as appendixes to this report. Appendix F, by Burton S. Snow, Sandia Laboratory, describes engineering and construction. Appendix G, by R. J. Burton, Sandia Laboratory, covers the arming and firing operation.

Toboggan was funded from the Plowshare program for Industrial Applications of Nuclear Explosives.

Frontispiece. Aerial View of Ditch C6a, Phase II, Toboggan

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SYMBOLS AND TERMINOLOGY

A	Area of ditch or crater at original ground surface in square feet
a	Ditch width in feet
C	$(\gamma_e - 1)^{-1}$ by definition
D	Ditch depth in feet
d	Crater depth in feet
e	Exponent used in scaling relationship (dim = Kw^e)
e_c	Energy released in cavity explosion (ft-lb)
DOB	Burial depth of charge in feet
K	Scaling constant (dim = Kw^e)
L	Ditch length in feet
L_e	Ditch length beyond end of linear charge in feet
p_c	Explosion pressure (lb/ft ²)
r	Crater radius in feet
2r	Crater diameter in feet
U	Explosive volume (ft ³)
V	Total ditch or crater volume in cubic feet
v	Total ditch or crater volume per pound of explosive (ft ³ /lb)
V_e	Volume of ditch per linear foot of explosive
W	Weight of spherical charge in pounds
<u>W</u>	Total weight of linear charge in pounds
w	Charge weight per unit length in pounds per foot
γ_e	"Effective" value of the ratio of the specific heats of gas in cavity
λ_{DOB}	Scaled burial depth of charge ($DOB/w^{1/2}$)
λ_l	Scaled distance from longitudinal axis of ditch to maximum lip height
λ_a	Scaled ditch width
λ_D	Scaled ditch depth
λ_d	Scaled crater depth
λ_r	Scaled crater radius

SYMBOLS AND TERMINOLOGY (cont)

λ_{2r}	Scaled crater diameter
λ_s	Scaled distance from charge
λ_v	Scaled crater or ditch volume (ft^3/lb)
ρ	Density
h_a	Maximum apparent lip height in feet
h_t	Maximum true lip height in feet
l_v	Volume of material in lip in cubic feet
m	Mass
Δ	Permanent vertical ground displacement measured at some distance from charge
X	Distance from edge of charge to displaced point
l	Distance from longitudinal axis of ditch to maximum lip height
a	Distance between detonator in the multidet system

As used in this report, a crater is that void or cavity which is created near the surface of a medium by a point charge. Craters were made only by the 8-pound TNT spheres included in this experiment. A ditch is that excavation or elongated cavity resulting from a linear charge. A trench is the excavation constructed by hand labor in which the linear charge is placed. Unless otherwise noted, all dimensions and volumes are for apparent craters and/or ditches. An apparent ditch or crater is readily observable immediately after the firing of an explosive charge. It is the apparent ditch which is of interest from an engineering excavation standpoint.

As opposed to the apparent ditch, the true ditch is that excavation remaining after fallback material has been removed. Figure 1 illustrates the difference between apparent and true craters and/or ditches.

Figure 1. Cross Section Through Ditch or Crater

SUMMARY

Project Toboggan was primarily an explosive ditching experiment. Linear TNT charges having square cross sections and yielding 0.23, 1.81, 10.8, and 42.7 pounds per foot were detonated in a relatively uniform, indurated clay medium. Explosive burst depth was increased until a depth required to obtain the optimum ditch for each charge weight was reached. Resulting ditches were carefully surveyed to determine their width, depth, and volume.

This experiment verified linear-charge scaling laws which had previously been developed. It should be noted that a valid scaling law prescribes the mathematical relationship existing between charge weights and their associated ditch dimensions. Thus a scaling law makes ditch dimensions from many linear-charge weights relative and, therefore, comparable. As expected, Toboggan ditch widths and depths varied directly as the square root of the linear-charge weight per foot, and volume per foot varied directly as the linear-charge weight per foot.

Toboggan ditching data were sufficiently extensive to establish depth-of-burst curves for width, depth, and volume. These curves indicated that ditch volume and width were optimum at a scaled burst depth of about 2.2, whereas ditch depth was optimum at a scaled charge depth of 1.5.

Several other interesting observations were made as part of the experiment. Permanent vertical displacement of the original ground surface measured along lines perpendicular to the longitudinal ditch axis at its midpoint varied as the negative 3.2 power of the scaled distance from the charge to the point of interest. Distance was scaled by the square root of the linear-charge weight per foot.

A few linear charges having circular cross sections were included to investigate the influence of charge shape. Dimensions of ditches created by these cylindrical charges were similar to those created by equivalent rectilinear charges. Significant variations attributable to the cross-sectional shape of the linear charges were not observed.

All charges in Phase I of Toboggan were end-detonated; those in Phase II were multidetonated. Thus the influence of detonation method could be observed. In general, end-detonated charges created ditches which were deeper and wider at the detonation end of the ditch. Fallback material was almost wholly lacking on the ground surface at the end opposite detonation. It was also interesting to note that very little fallback material was observed on the surface at either end of ditches created by multidetonated charges.

Prior to Toboggan, several ditches were made in the Yucca Lake medium by detonation of equally spaced 8-pound spheres of TNT. The dimensions of these ditches compare favorably with the Toboggan ditch dimensions when the point charges are reduced to an equivalent line charge and scaled accordingly.

Also included as part of Toboggan were point-charge cratering shots, the charges for which were 8-pound TNT spheres. Data from these shots permitted development of complete depth-of-burst curves. Thus, for the first time, the relationship between point- and line-charge craters and/or ditches in a single medium is available. If it can be assumed that the relationship between line- and point-charge craters and/or ditches is the same for all media, then a line-charge ditch can be deduced for any medium in which a few

point-charge craters have been created. One recommendation resulting from Project Toboggan is that this assumption be tested. The other is that for any Plowshare ditching application utilizing HE line-charge equivalent of rows of nuclear explosives, the scaled burst depth be within the range 1.5 to 2.2.

CHAPTER I -- INTRODUCTION AND BACKGROUND

Project Toboggan consisted of a series of linear and spherical high-explosive (HE) charges fired in the playa* forming the Yucca dry lake bed at the Nevada Test Site. All shots in Phase I, conducted in the fall of 1959, were end-detonated. Phase II shots, conducted during the spring of 1960, were multidetonated. Toboggan was carried out primarily for the acquisition of information on ditching with HE linear charges. These data may be compared later with those of rows of single charges whose craters might be extrapolated to nuclear row charge yields, thus providing significant data for the Plowshare program.

Specific objectives which apply to both phases of Toboggan were (a) to define apparent ditch parameters of width, depth, and volume as a function of burst depth in a relatively homogeneous medium; (b) to determine acceptability of square-root scaling (linear dimensions proportional to $(\text{pounds/foot})^{1/2}$)[†] over the range of explosive weights used; and (c) to observe and compare linear- and point-charge earth-moving capability in the same medium. A cylindrical charge was included in Phase II to determine if there were detectable effects due to the cross-sectional shape of the linear charge. The effect of detonation method was determined by comparing similar ditches fired during Phase I and Phase II.

Ditches have been excavated with high explosives for several decades. Past experience has shown this technique to be useful under certain field conditions which preclude use of conventional digging equipment. In one instance dynamite was used on a large-scale ditching basis to reclaim a swamp for a banana plantation in Honduras.¹ Explosive ditching methods for such projects as flood control, pipelines, highway construction, and others are described in detail in a publication of the duPont Company.² It was recommended for each of these ditching cases that the explosive be placed in equally spaced holes. In essence, the explosive charge creating the ditch consists of a series of cylindrical charges detonated by propagation or, individually, by electric caps, depending on the medium. Several charge placement configurations are given. An exhaustive literature search has failed to uncover a single instance of industrial ditching using linear charges.

Very little prior work or experimentation has been done on explosive ditching with linear charges. In 1946 Fraenkel and Kennedy, reporting on air blast from linear charges, included some data on ditches from linear charges.³ Eleven types of charges which utilized four different explosives were detonated. The medium was a sandy-clay loam. Measurements of apparent ditch widths and depths were made. Charge weight varied from less than 0.1 to about 15 pounds per foot.

* The shallow central basin of a desert plain, in which rain water gathers and evaporates.

† Throughout this report, unless otherwise noted, ditch dimensions are scaled by the square root of the linear charge weight per foot.

In 1958, Sandia Corporation undertook a linear explosive ditching experiment to determine apparent ditch parameters as a function of burst depth.⁴ Twenty-eight shots were fired in a single medium, fan delta alluvium, in Sandia's Coyote Canyon test facility. Three explosives, yielding 0.15, 1.8, and 10.8 pounds per foot were detonated at scaled burst depths^{*} ranging from 0.0 to 1.4. Only a few shots were end-detonated. The experiment was limited by the size of available test facilities.

The current linear ditching series in Nevada supplements and expands the prior work done by Sandia. The scope of this investigation, as shown in Table I, is greater than for any similar experiment of which we are aware. An attempt has been made to reduce data scatter by conducting the experiment in the most homogeneous medium available. The range over which it was conducted was such that scaling exponents and depth-of-burst curves can be accepted with a high degree of confidence for the Yucca Lake playa.

Figure 2 is a sketch map showing the Toboggan ditch layout for Yucca Lake.

TABLE I
Summary of Toboggan Shots

	Scaled Depth of Burst (ft/w ^{1/2})	Linear Explosive Yield (lbs/ft)					
		0.23	1.81	10.8	10.8 (cyl)	42.7	8 [†]
Phase I	0.0	xx	xxx	xxx		xxx	xxx
	0.25	xx	xxx	xxx		xxx	xxx
	0.50	xx	xxx	xxx		xx	xxx
	1.0		xxx	x			xxx
	1.5		xxx				xxx
	2.0		xxx				xxx
Phase II	0.0	xx	x	xx	xxx	x	
	0.25	xx	x	xx		x	
	0.50	xx	x	xx		x	
	1.0	xx	x	xx	xxx	x	
	1.5	xx	x	xx		x	
	2.0	xx	x	xx	xx	x	
	2.5	xx	x	xx		x	
	3.0	xx	x	xx		x	

[†]This explosive is an 8-pound TNT sphere.

Six additional spheres were fired during Phase II of Toboggan at scaled burst depths of 0.75, 1.25 (2), 1.75, 2.25 and 2.50.

^{*}Scaled burst depth for a linear charge is determined by dividing actual burst depth in feet by the square root of the linear charge weight in pounds.

Figure 2. Ditch Layout Map of Toboggan Area

CHAPTER II -- EXPLOSIVE CHARGES AND FIRING SYSTEMS

Project Toboggan explosives consisted of three weights of linear charges having square cross sections, one linear charge having a circular cross section, one linear charge made up of four primacord strands, and a single-weight spherical charge. All ditches and craters were formed in the same medium. Figure 3 gives the project experiment summary. The ditch and shot numbering system used throughout this report employs capital letter values for explosive weights per foot; (e. g., A = 1.81, B = 10.8, C = 42.7, D = 0.23, E = sphere, F = cylinder = 10.8). Lower case letters are used to designate different shots of the same yield and same depth of burst. Numbers designating scaled burial depths are as follows:

1	= 0	5	= 1.5
2	= 0.25	*5.5	= 1.75
3	= 0.50	6	= 2.0
*3.5	= 0.75	*6.5	= 2.25
4	= 1.0	7	= 2.5
*4.5	= 1.25	8	= 3.0

Only 8-pound spheres were detonated at the asterisked (*) fractional burst depths shown.

The explosive for charges A, B, C, E, and F was TNT (trinitrotoluene). All were cast TNT except for charge A which was pressed TNT. The explosive core in charge D, the special primacord charge, was PETN (pentaerythrite tetranitrate).

TNT has a yellow crystalline structure consisting of $C_6H_2(CH_3)(NO_2)_3$. It explodes at 240° to $280^{\circ}F$ and its melting point is about $180^{\circ}F$. Its detonation velocity varies directly with density and, at a density of 1.6, it has a detonation rate of about 23,000 feet per second. Pressed TNT (Explosive A) has a density which is less than cast TNT. Measurements made on Toboggan explosives indicated densities of about 1.6 for the cast TNT and 1.4 for the pressed TNT. Detonation rate of the pressed TNT was about 2000 ft/sec less than for the cast TNT: 21,000 ft/sec pressed, 23,000 ft/sec cast. Detonation pressure for pressed TNT is approximately 1.7×10^6 to 1.8×10^6 psi, while for cast TNT this pressure is 2.25×10^6 psi.

PETN is fine, light-colored granular powder consisting of $C(CH_2ONO_2)_4$, which has a melting point of $141^{\circ}F$ and a density of about 1.63; its detonation velocity is around 27,000 feet per second.

Explosive A

This charge was a standard military demolition block having a weight of 1.81 pounds per linear foot. Two 1/2-pound blocks, 1-7/8 x 1-7/8 x 3-5/16 inches, were packaged in a cardboard container having metal ends. The explosive blocks were removed from this container before placement. The bare TNT blocks were placed end to end to form the linear charge of length required.

Explosive B

This charge was a cast TNT block weighing 10.8 pounds per linear foot and measuring 4 x 4 x 11 inches. The linear charge was made by placing the bare TNT blocks end to end. The charge for ditch B4a of Phase I and all B-charges of Phase II were made up of cast TNT explosive blocks, 2 x 4 x 12 inches, placed side by

Figure 3. Toboggan Experimental Summary

side to make up the 4- x 4-inch cross section. The explosive weight per linear foot was the same as that for the 4- x 4- x 11-inch blocks.

Explosive C

This linear charge was made up of cast TNT blocks weighing 42.7 pounds per linear foot. An 8- x 8-inch cross section was built of TNT blocks as shown in the sketch below:

The individual small blocks were wrapped in thin waxed paper, and all blocks making the cross section were held together with tape. Tape and paper remained on all C charges at the time of firing.

Explosive D

This linear charge was made up of four strands of a special primacord, each strand having a weight of 400 grains per foot and a diameter of 0.425 inch. The primacord covering consisted of a polyethelyene plastic, high-tenacity rayon, and a coating of asphalt. The cumulative weight of the explosive in the four strands was about 0.23 pound per linear foot. The primacord was taped together to yield a cross section as shown below:

Explosive E

This charge was used to excavate craters rather than ditches. It consisted of a sphere of cast TNT weighing 8 pounds and having a radius of 3 inches.

Explosive F

This charge was a cylindrical TNT block having the same linear yield as Explosive B (10.8 pounds per foot). Its cross section had a diameter of about 4-1/2 inches. These charges were specially ordered for the Toboggan experiment.

Firing Circuit for Phase I

A schematic diagram of the circuit used to fire linear charges during Phase I is shown in Figure 4. All charges described were end-detonated at the north end of the charge by a duPont jet perforator (i. e., a shaped charge having a plastic body, a copper-lined cone, and containing about an ounce of RDX). This unit, originally designed for perforating oil well casings, was securely taped to the end block of the linear charge and directed vertically downward. A No. 8 electric blasting cap was taped between two strands of plain 49-grain-per-foot primacord which was in turn threaded through the eye of the jet perforator. The electrical current used to fire the blasting cap was generated with a No. 10 Twist Blasting Machine designed to fire ten electric blasting caps in series.

Firing Circuit for Phase II

A diagram of the circuit used to fire the linear charges during Phase II is shown in Figure 5. All charges were detonated at eight points simultaneously. High-speed motion-picture photography of the multi-detonation system firing caps proved that all eight detonators in the system fired within about 1/6 of a milli-second.

The eight detonators were placed in such a manner that all detonation waves traveled the same distance within the HE. Relative placement of the detonators on the linear charge is shown below.

The shortest charge (D1a) was 4 feet. At a detonation velocity of 27,000 ft/sec, total detonation was accomplished in 9.2 microseconds. The longest charge (C8a) was 201 feet. At a detonation rate of 22,000 ft/sec total detonation was accomplished for the latter shot in 570 microseconds.

Detonators (duPont jet perforator), electric blasting caps, and primacord used in the multidetonation system were the same as described for the system used during Phase I. Power required for firing the 8 detonators was supplied by a portable generator located at the firing site.

Figure 4. Linear Charge Firing Circuit Used During Phase I

Figure 5. Linear Charge Firing Circuit Used During Phase II

CHAPTER III -- MEDIUM

The playa making up the Yucca dry lake bed consists of compact fine silt and clay that is extremely uniform both laterally and vertically. The Yucca dry lake typifies the many playa basins found in southwestern United States. The playa deposit represents the end product of erosion, and thus the lake bed is an area of deposition which is still gradually being filled. Deposition occurs during and following torrential rain storms and floods. Fine material is transported by the surface water across the gentle valley slopes which completely surround the playa basin. Water completely covers the Yucca Lake bed several times each year. It was covered for about two months between Phase I and II of Project Toboggan.

The mud-cracked playa surface is characterized by its over-all smoothness; variations of elevation were within 0.2 feet over the experimental area of Toboggan. The thickness of the playa deposit varies and has a maximum depth estimated to be about 100 feet.

A detailed soils investigation was conducted as part of Phase II. Tests were made to determine grain size, moisture content, density, compaction, consolidation, and triaxial compression. These determinations were made on specimens removed from a test pit located at roughly the geometric center of the Toboggan test area. Complete results of the soils survey are presented in Appendix A.

A visual inspection of HE placement trenches indicated a 6- to 8-inch surface stratum in the playa. This layer is probably the result of variations caused by moisture, inasmuch as the lake bed is occasionally covered with water. When the area is flooded, the low vertical permeability of the playa medium prevents water removal by means other than evaporation.

It should be noted that complete uniformity was not observed in the sequential strata profile which exists over the entire test area. Various sand and gravel lenses discovered in one trench were not necessarily found in another trench at the same depth. It appears that the rate of deposition for the Yucca Lake playa has fluctuated significantly during its geologic history.

The following tabulation shows classification of the medium at various depths. This classification is based on grain size distribution as developed by the U. S. Bureau of Soils Textural Classification.

Yucca Lake Soil Classification

<u>Sample depth</u> <u>(ft)</u>	<u>Sand</u> <u>(%)</u>	<u>Silt</u> <u>(%)</u>	<u>Clay</u> <u>(%)</u>	<u>Classification</u>
0.5	12	15	73	Clay
2.5	24	43	33	Clay
4.5	21	39	40	Clay
6.5	50	21	29	Sandy clay loam
10.5	83	6	11	Sand
14.5	17	27	56	Clay
17.5	58	20	22	Sandy clay loam
20.5	51	26	23	Sandy clay loam

Other classification techniques are available; however, sufficient tests were not performed on the Yucca material to use them.⁵

Classifications and percentages given in the tabulation indicate that the characteristic behavior and properties of the Yucca Lake medium would be as expected for a classical or sandy clay.

Several density and moisture content determinations were made in situ slightly below the surface and near the geometric centers of the Toboggan area. The first such test, made in October of 1959, yielded a wet density of 81.4 lb/ft³, a dry density of 75.0 lbs/ft³, and a moisture content of 8.5 percent. In late March 1960, after the winter rains, moisture content at the October test location was 11.5 percent.

In May, at the same location as prior tests, wet density was found to be 84.6 lbs/ft³, dry density to be 75.7 lbs/ft³, and moisture content 12 percent. Moisture contents determined on specimens taken at various depths in the test pit ranged from 8.1 to 19.8 percent. Wet densities ranged from 64.4 to 90.3 lbs/ft³, dry densities from 59.3 to 75.5 lbs/ft³.

These variations in density and moisture content are within an expected range when studied in the light of variations generally encountered in soil exploratory work.

CHAPTER IV -- EXPERIMENTAL PROCEDURE

Rigid control was exercised over each operational phase of Project Toboggan. An attempt was made to follow a field ditch layout in order that trench excavation and HE placement could continue while the engineering survey was being conducted on the most recently created ditch. Dimensions of HE placement trenches were held to a minimum and were excavated only to the size necessary for the linear charge to be placed.

After completion of each HE trench, laborers and all personnel not directly engaged in HE placement were removed from the site. HE placement was performed by experienced handlers. Each charge was carefully positioned and leveled at the required burst depth. Care was exercised to ascertain that charge blocks were placed in direct end-to-end contact with each other in order that misfires be held to a minimum. A dry sand cushion was used to fill in beneath, on both sides of, and over the charge to a depth of about 2 inches. Backfill material and procedure for the remainder of the trench were carefully controlled in an attempt to restore as much as possible the in situ condition.

The backfill material consisted of a mixture of water and native material removed in excavation of the trench. Mixing was done by hand along the edge of the trench during Phase I and by heavy equipment during Phase II. The procedure recommended by the Holmes and Narver soils engineer consisted of mixing until the material just crumbled when squeezed gently by hand. The backfill was then placed in 6-inch lifts and tamped by mechanical air-driven tampers. The backfill procedure finally accepted proved to be satisfactory, as evidenced by the result of several actual backfill density and moisture content determinations. Results of these tests are given in Table B.4 of Appendix B.

Excess soil material was removed after backfill was completed. The site was then barricaded and left for a minimum of 24 hours before firing the HE.

Safety problems were encountered for the larger ditches. It was necessary to shore up the walls of any trench deeper than about 10 feet. All large trenches included in Phase II were excavated by a mechanical ditchdigger.

The surveying crew was the first to return to a newly created ditch after the "all clear" was given by the HE handlers. The crew's immediate task was to relocate survey points and stretch string lines over the ditch for the photographers. Walking on fallback from the ditch was held to a minimum.

Photographers waited until string lines were in position before making a permanent record of the ditch. Overhead photos were taken from directly over the ditch with the aid of a hydalift. A few of the large C-ditches were photographed from a helicopter. The hydalift height range was limited to about 30 feet; thus it was difficult to make either meaningful single or mosaic photographs of the larger ditches. A 4- x 5-inch Crown Graphic camera was used for all black and white still photography. Footprints and vehicle tracks were held to a minimum in the ditch and in the immediate surrounding area until after all ditch measurements and photographs had been made.

Surveyors took readings on surfaces undisturbed after the shot. The rodman was permitted to walk only on that surface of the ditch which had been previously recorded with the leveling rod.

A 20-mile-per-hour wind was the upper limit acceptable for firing. Since the weather was exceptionally good during the entire operation, many shots were fired in winds of 5 miles per hour or less. Wind data were obtained from the U. S. Weather Bureau Field Station near the northwest edge of Yucca Lake.

Work was so scheduled that survey followup was made within 24 hours after creation of a ditch. Photographic followup was made immediately. A photographic sequence of experimental procedure is shown in Figure 6.

① EXCAVATION OF LINEAR
HE TRENCHES

② PLACEMENT OF THE HE

④ BACKFILLING

③ HE IN POSITION

Figure 6. Photographic Sequence Showing Experimental Procedure

Figure 6. Photographic Sequence Showing Experimental Procedure (cont)

CHAPTER V -- MEASUREMENTS

Primary data for the ditching experiment were secured from precision surveying done by the Holmes and Narver survey party.

Survey

Each ditch was carefully surveyed as soon as possible after it was created. Each potential ditch location was presurveyed to establish the original ground datum plane and control points for the postshot survey. (Except for isolated spots, variations over the entire experimental area are less than 0.2 foot.) Hundreds of elevations were taken for each ditch. Elevation points were chosen to reflect surface differences of 0.1 foot.

The survey notes were used in the making of contour maps (Figure 7) of each ditch and were so complete that, in several cases, it was possible to establish a contour interval for the lip of the D (primacord) ditches of 0.01 foot. The contour interval was varied, however, depending on the size of the ditch. Original experiment requirements called for a topographic map of each ditch, having at least six equal contour intervals within the ditch and two contours of the crater lip. Accuracy of about ± 10 percent of the contour interval was called for; this requirement was met.

Data reduced for this report were ditch width, depth, and volume. Only the apparent ditch was considered. The center one-third of the ditch was used to avoid variations in ditch shape caused by end and detonator effects. Average ditch width, a , was obtained by measuring the area of the center one-third of the ditch contour at original ground surface with a planimeter and dividing this value by the length of the center one-third of the ditch. Average ditch depth, D , was found in the same way; the area measured was the center one-third of the longitudinal ditch profile. Apparent ditch volume, V , was found by summing the computed volumes between consecutive ditch contours, again using the center one-third of the ditch.

Permanent displacement measurements were made for several ditches. Spikes were driven flush with the ground surface along lines either normal to or coincident with the longitudinal ditch axis. Vertical movements were determined for these spikes by preshot and postshot level surveys.

Photography

Documentary still photographs were taken of all ditches. An attempt was made to photograph each ditch from directly overhead; however, boomlength limitations of the hydalift prevented photos of the large ditches. A survey rod and 1-foot scaling squares were in the field of view for each overhead ditch shot. String lines in each photo established the longitudinal axis of each ditch and the ends of the linear charge used to create the ditch. A title board listing shot number, date, charge depth, charge length, and total explosive weight was also in the field of view. In addition, several oblique photos were taken of each ditch.

Ditches C4a, C5a, C6a, and C7a were photographed from a helicopter. The length of the hydalift boom prohibited photographing these large ditches in the conventional way.

Ditches C2a, C3a, and C4a were covered by motion picture photography. The cameras viewed the longitudinal side of each ditch. Targets were placed over the detonator points and a backboard was constructed behind the ditch. Thus it was possible to record ground movement over the charge at a very early time. All three ditches were photographed by a 35-mm, half-frame Fastax camera, running at 5000 frames per second. A 16-mm camera was also used on ditches C2a and C3a. On shot C4a, a Photosonic camera, running at 500 frames per second, was used to observe the south end of the ditch; a Warrick camera, running at 1400 frames per second, was used to determine early ground motion over the charge.

An extensive crack pattern investigation was made by personnel of the Lawrence Radiation Laboratory and, at this writing, it is anticipated that a report will be issued by LRL in the near future.

Figure 7. Typical Sections Made from Field Survey Notes

Figure 7. Typical Contour Map Made from Field Survey Notes (cont)

CHAPTER VI -- EXPERIMENTAL RESULTS AND INTERPRETATION

Data Log

Data for all linear ditching shots fired in Phases I and II are given in Appendix B. Ditch width and depth are apparent dimensions. Volume given is for the entire ditch.

In several cases it may be noted that explosive length is somewhat greater than would be calculated by use of total explosive charge weight and explosive yield per foot. This occurs, since it is not possible to place charges end to end without some small loss in usable trench length. This loss in length is most pronounced for the C explosive because of the wax paper covering and the relatively long length of total charge. Even for this charge, however, increase in total length is negligible when compared to total charge length.

Scaling

Rigid scaling laws for high-explosive craters are not readily apparent. However, certain concepts which obviously support experimental scaling data may be mentioned. It seems obvious that the distance from any charge center to its resulting crater boundary is determined by some critical stress ensuing from the explosion.

The stress or pressure which results at the charge surface from a sudden release of chemical energy can be shown to be constant for TNT charges having equal densities. This derivation* is given below:

$$p_c U = \frac{e_c}{C}, \quad (1)$$

where p_c = explosion pressure (lb/ft²)

U = explosive volume (ft³)

e_c = energy released in cavity explosion (ft-lbs)

$C = (\gamma_e - 1)^{-1}$ by definition

γ_e = "effective" value of the ratio of the specific heats of gas in the cavity.

Now

$$\rho = \frac{m}{U},$$

where m and ρ are mass and density of the TNT, respectively. Substituting in Equation 1, above,

$$p_c = \frac{e_c \rho}{mC} = \frac{e_c}{m} \rho C^{-1}. \quad (2)$$

*By R. H. Bishop, Sandia Corporation.

This expression indicates that charge surface pressure is a function only of charge density. The value C^{-1} is about 0.43 for a chemical explosion. Using 81.2 pounds per cubic foot as the density and an explosion energy release by one pound of TNT, $\frac{e_c}{m}$, of about $15.4 (10^5)$ ft-lbs/lb of TNT, an equilibrium pressure of 373,000 psi can be calculated. The significant observation that can be made here is that equilibrium pressure of a particular TNT charge is equal to that of any other TNT charge if their densities are equal. The starting pressure for chemical explosive is not dependent on charge yield.⁶

Thus the scaling concept becomes apparent. A spherical charge W_1 will have an equilibrium pressure at its radius r_1 . The same equilibrium pressure would exist for another spherical charge, W_2 , of the same density, at a distance

$$r_2 = \left[\frac{W_2}{W_1} \right]^{1/3} r_1.$$

Thus, the same equilibrium pressure obtains at explosive boundaries, regardless of total weight. It would be expected that the distance decay of these pressures (i. e., neglecting effect of time histories for different size charges) would be geometrically similar. Accordingly, for spherical charges, it would be presumed that cube-root scaling should prevail.

The difference between spherical and line charges lies in radius dependence on volume. Considering only infinite line charges, radius varies directly as the square root of the volume per unit length. Then, by the same reasoning as used for spherical charges, it would be expected that the pressure would scale by the square root of charge weight per unit length for infinitely long linear charges.

It should be noted here that equilibrium pressure dependence on TNT density could serve to explain scaling differences noted between ditches created by pressed TNT (A explosive) and the other charges used in Toboggan. The A explosive had a lesser density and, as would be expected, showed consistently lesser values for the various ditching quantities.

Several methods of correlation were used to determine scaling for Toboggan ditching data. Individual straight line fits were made to the scaling plots for ditch width, depth, and volume for each scaled burst depth. The fitting method was a least squares procedure after Quenouille.¹¹ Mathematical aspects of the fitting problem are explained in Appendix C. Figure 8 gives results of the individual straight line treatment.

A mathematical treatment was also made to determine the best family of straight lines which could be fitted to the scaling plots. This determination was made for all Toboggan data, for Phase I data (end-detonated charges), and for Phase II data (multidetonated charges). Figure 9 shows the result of fitting the best family of straight lines to the scaling plots.

Figure 8. Individual Straight-Line Fits to Scaling Plots

Figure 9. Families of Straight Lines Fitted to Scaling Plots of All Toboggan Data

Table II summarizes results from all scaling calculations. Scaled burst depths of 0, 0.25, and 0.50 only were available from Phase I. The scaling function is of the form: $\text{dim} = K w^e$, where "dim" refers to volume, width, or depth, K is a constant, and e is the scaling exponent.

TABLE II
Summary of Scaling Relationships for Toboggan Data *

		Phase I End-detonated charges							
Scaled Depth-of-Burst, DOB/w ^{1/2}		0.0	0.25	0.50	1.0	1.5	2.0	2.5	3.0
Ditch Width e = 0.528	K	1.70	2.61	3.68	--	--	--	--	--
Ditch Depth e = 0.491	K	0.325	0.673	0.845	--	--	--	--	--
Ditch Volume e = 1.01	K	0.317	0.996	1.97	--	--	--	--	--
		Phase II Multidetonated charges							
Ditch Width e = 0.495	K	1.90	2.86	3.58	4.99	5.60	6.15	5.57	5.42
Ditch Depth e = 0.571	K	0.277	0.583	0.706	1.15	1.39	1.15	0.870	0.524
Ditch Volume e = 1.01	K	0.292	0.846	1.47	3.41	4.01	5.61	4.21	2.71
		All Toboggan Data Individual straight line fits at each burst depth							
Ditch Width	K	1.89	2.69	3.68	5.01	5.38	5.82	5.25	5.60
	e	0.479	0.523	0.532	0.464	0.517	0.520	0.567	0.479
Ditch Depth	K	0.293	0.625	0.828	1.32	1.54	1.21	0.779	0.378
	e	0.548	0.442	0.479	0.475	0.511	0.535	0.639	0.825
Ditch Volume	K	0.310	0.970	1.77	3.53	3.90	5.64	3.97	2.64
	e	1.00	0.988	1.02	0.970	1.09	0.990	1.07	1.04
		All Toboggan Data Family of parallel lines fitted to data							
Ditch Width e = 0.510	K	1.81	2.74	3.78	4.71	5.42	5.90	5.57	5.42
Ditch Depth e = 0.496	K	0.317	0.581	0.811	1.28	1.56	1.27	--	--
Ditch Volume e = 1.01	K	0.306	0.937	1.78	3.33	4.19	5.49	4.21	2.71

NOTE: Scaling function is of the form: $\text{dim} = K w^e$
where dim = volume, depth or width
K = constant
w = linear yield of TNT in pounds
e = scaling exponent

* Refer to Appendix A of the interim report for mathematical analysis of Phase I data; refer to Appendix C of this report for mathematical analysis for Phase II and combined Phase I and II data.

Ditch depth shows the greatest departure from square-root scaling when straight line fits are made to data at scaled burst depths of 2.5 and 3.0. It can also be shown mathematically that when an attempt is made to fit a family of straight parallel lines to all Toboggan depth data, the lines for burst depths of 2.5 and 3.0 are not members of the parallel line family (see Appendix C). The scaling exponent for other ditch quantities at all burst depths included in this experiment, regardless of the data fitting technique used, does not depart significantly from that which would be expected, i.e., 1.0 for volumes and 0.5 for width.

The significant variation which is evidenced by the straight line fit to the scaling plot for ditch depth is due to several factors. It has been shown that gravitational forces may be influential in changing the scaling exponent for spherical charges.⁷ Haskell found that when depth data for a number of different yield surface charges were plotted for the same depth of burst (surface DOB) the scaling exponent appeared to be less than that which would be expected ($1/4$ instead of the usual $1/3$). In other words, gravitational forces would be less influential in changing dimensions of craters from smaller charges than from larger ones. However, variation for Toboggan depth data was in a direction opposite that observed by Haskell; i.e., the scaling exponent was greater than the expected $1/2$ for scaled burst depths of 2.5 and 3.0. If gravitational forces were responsible for this variation, it might be concluded that such forces were not significant until optimum burst depth was reached, and that then these forces would be more influential in creating greater depths for those ditches resulting from large linear charges than for those resulting from small ones. Thus, it appears that Toboggan ditch depth variations cannot be attributed to gravitational forces.

There is another factor which may aid in explaining the apparent variation in scaling exponent for ditch depth. It was observed that at a scaled burst depth of 3.0 the A explosive created ditches which were characterized by mounds along the longitudinal ditch axis, mounds which had a maximum elevation well above the original ground surface. At the same scaled burst depth, B, C, and D explosives created clean ditches. As mentioned previously, the A explosive was pressed TNT, the B and C explosives were cast TNT, and the D explosive was PETN. Detonation velocities were approximately 21,000, 23,000, 23,000, and 27,000 ft/sec, respectively. If it is assumed that the efficiency in creating ditch depth is directly dependent on detonation velocity, it would be expected that ditch depth data points for the A explosive would fall below the $1/2$ -slope scaling line, and the D explosive ditch depth data points should be above this line. The A explosive points did appear to fall consistently below the straight lines which were best fitted to the data for depths of burst of 2.0 and below. If the assumption made above is valid, it appears that the greater efficiency of the D explosive (D explosive has a lesser charge weight than A explosive) is compensated by the lesser efficiency of the A explosive, and a square-root scaling relationship results for all data. It is difficult to explain why this same compensation would not result in square-root scaling at depths of burst of 2.5 and 3.0

The Fraenkel and Kennedy military line charge data³ for surface-burst linear charges reveal a width-yield relationship of $a = 2.44 w^{0.50}$ and a depth-yield relationship of $D = 0.67 w^{0.35}$ when straight lines are fitted to the data by the Quenouille method. These military line charge data are included in Appendix D. The Sandia linear ditching experiment⁴ resulted in width, a , equal to $1.3 w^{1/2}$, whereas depth, D , equaled $0.4 w^{1/2}$. These Sandia relationships were developed by visually fitting the $1/2$ -slope line to the data for surface-burst charges.

Using the straight-line family fit for all Toboggan data shown in Figure 9, it is possible to develop empirical expressions which relate scaled burst depth and linear charge yield to ditch width, depth, and volume. A second degree polynomial has been fitted to the plot of K versus scaled burst depth for each ditch parameter. (See Appendix C for mathematical aspects of this development.) Figure 10 shows a plot of the derived polynomials and the actual values of K for the various depths of burst. Ditch parameter relationships are given below:

$$\text{Volume} = (-1.1 \lambda_{\text{DOB}}^2 + 4.3 \lambda_{\text{DOB}} + 0.09) w^{1.0}$$

$$\text{Width} = (-0.83 \lambda_{\text{DOB}}^2 + 3.6 \lambda_{\text{DOB}} + 1.9) w^{0.53}$$

$$\text{Depth} = (-0.51 \lambda_{\text{DOB}}^2 + 1.5 \lambda_{\text{DOB}} + 0.25) w^{0.49}$$

It should be emphasized that depth of burst is a scaled quantity. It is obtained by dividing the actual charge burial depth by the square root of the linear charge yield. Limits on this depth of burst are 0 to 3.0 for ditch volume and width, and 0 to 2.0 for ditch depths; these limits are inclusive.

Depth-of-Burst Relationships for Linear Charges

Depth-of-burst relationship for ditch width, depth, and volume is shown in Figure 11. As indicated by the scaling plots, ditch width and depth have been scaled by the square root of the charge yield in pounds. Ditch volume is given on a unit yield basis, and a polynomial fit has been made to these data. All Toboggan data are included. In each case the polynomial, which is mathematically the best fit, is shown. (See Appendix C.) It should be noted that the significance of the polynomial as a functional relationship is only in the correlation of data points in a consistent manner. Table III gives significant quantities for each of the depth-of-burst plots.

TABLE III
Depth-of-Burst Quantities for Linear Explosive Ditches

	Width (ft/w ^{1/2})	Depth (ft/w ^{1/2})	Volume (ft ³ /w)
Optimum scaled DOB	2.2	1.5	2.2
Value of ditch quantity at optimum	6.0	1.5	5.2
Value of ditch quantity for surface bursts	2.0	0.3	0.3

Figure 12 shows actual depth-of-burst relationships for the width and depth of explosive D ditches. Overhead photographs printed to approximately the same scale are shown to illustrate the increase in ditching efficiency as the D explosive is buried at deeper depths.

Figure 10. Constant "K" Plotted Versus Scaled Burst Depth

Figure 11. Depth-of-Burst Relationships for Ditch Width, Depth, and Volume

Figure 12. Actual Ditch Width and Depth Versus Charge Burst Depth for Explosive D

Depth-of-Burst Relationships for Spherical Charges

For comparison, a series of 8-pound spheres was detonated in Yucca Dry Lake. Figure 13 shows scaled depth-of-burst relationships for resulting craters and a plot of actual crater depth and diameter data as functions of actual burst depth is given in Figure 14. Crater depths and diameters have been scaled by the cube root of the spherical charge weight. Crater volume is presented on a volume-per-pound basis. Data for each crater quantity have been fitted with a polynomial. The degree of polynomial to be chosen was determined by mathematical analysis (see Appendix C). Again it should be noted that the polynomial as a functional relationship was only selected to treat the data with some degree of uniformity and it has no theoretical basis. All Toboggan spherical charge data are included. Table IV gives significant values for each crater quantity.

TABLE IV
Depth-of-Burst Quantities for Spherical Charge Craters

	Diameter (ft/W ^{1/3})	Depth (ft/W ^{1/3})	Volume (ft ³ /W)
Optimum scaled DOB	1.1	0.7	1.1
Value of ditch quantity at optimum	3.7	0.89	3.5
Value of ditch quantity for surface bursts	1.3	0.32	0.3
Scaled DOB at containment*	2.5	2.5	2.5

* At this burst depth no measurable volume would be found using the data reduction techniques of Toboggan.

It is of particular interest to compare burst-depth curves for spherical charges with those for linear charges. Such a comparison would prove extremely useful if it could be made generally applicable.

There are several possible ways of making such a comparison. One method would be that of directly comparing burst-depth curves for 1-pound spherical charges with similar curves for linear charges of 1 pound per foot, which is to say superimposing the curves of Figures 11 and 13. However, this would be misleading, particularly at the greater burst depths, since it might be concluded that linear charges would be much more efficient to use than spherical charges. This may or may not be so, but this particular comparison doesn't prove the point either way. The comparison is relatively meaningless, since the two curves are scaled in different ways.

Another and more interesting comparison is presented in Figure 15. Here actual burst-depth curves for a linear charge of 0.05 pound per foot and for a spherical charge of 0.05 pound are compared. At these charge yields, optimum values of ditch width and crater diameter are nearly equal, as are ditch and crater depth. Also, at this yield, optimum values for the spherical charge occur at burst depths which are 0.8 of the linear charge depth.

DIAMETER

DEPTH

VOLUME

Figure 13. Scaled Crater Diameter, Depth, and Volume as a Function of Charge Burial Depth

Figure 14. Actual Crater Diameter and Depth as a Function of Actual Burst Depth

Figure 15. Actual Burst-Depth Curves for Spherical and Linear Charges

$$\text{Optimum ditch width} = 1.35 \left[\frac{W}{0.05} \right]^{1/2}$$

(1.35 ordinate value on combined curve)

$$\text{Depth of burst at optimum ditch width} = 0.475 \left[\frac{W}{0.05} \right]^{1/2}$$

(0.475 abscissa value for linear charge)

$$\text{Optimum crater diameter} = 1.35 \left[\frac{W}{0.05} \right]^{1/3}$$

$$\text{Depth of burst at optimum crater diameter} = 0.38 \left[\frac{W}{0.05} \right]^{1/3}$$

(0.38 abscissa value for spherical charge, or this value can be derived by taking 8/10 of abscissa value for linear charge at optimum.)

Similar relationships would hold in the utilization of a combined curve for crater and ditch depth data.

The volume curves are consistent with those for width and depth. If it is assumed that the crater is a paraboloid of revolution and that the cross section of the ditch is a parabola, in this instance where widths and depths are equal, the ratio of the crater volume to the ditch volume per foot should be $3\pi/16$ or 0.59 times the crater diameter. The ratio of volumes as obtained experimentally is about half the crater diameter. The difference can be attributed in part to shapes that are not exactly paraboloidal and, in part to the crudeness of the estimate.

It is always possible to find a charge size and a depth ratio by use of which the maxima of two such curves can be made to coincide, since this corresponds to simple linear compressions or expansions of the ordinates and abscissae. What is really remarkable in Figure 15, is that the same two numbers fit both sets of curves together and, moreover, make them fit well everywhere and not just at their maxima.

It may be that burst-depth curves for spherical charges and linear charges can generally be fitted together in this manner and, if so, it will be a very powerful generalization. However, the relationships indicated have only been demonstrated in Yucca Lake clay and remain to be shown for other media. In any case, it would be too much to hope for exactly the same numbers to be useful elsewhere.

Detonation Effects

The most striking examples of detonation effects were evidenced in the ditches which resulted during Phase I. All charges fired during this phase were end-detonated and used the firing system shown in Figure 4. The main effect of this detonation technique was evidenced by the shape of the resulting ditch at the detonation end and by the peculiar distribution of fallback debris at the end opposite detonation. The shape effect, a "bulb"-shaped excavation at the detonation end of the ditch, was also observed for the Sandia ditches.⁴ A number of ditches showed greater depth at the detonation end; other ditches exhibited greater width. Several striking examples were observed of the complete lack of fallback beyond a line normal to the ditch axis at the end opposite detonation. Also noted were ditches having a depressed original ground surface at the end opposite detonation. Figure 16 shows typical examples of these end-detonation effects.

Figure 16. Typical End-Detonation Effects

Another effect of end-detonation was noticed for ditch length measured beyond the end of the original charge. Generally, this length was significantly greater at the detonation end. On the average, for the A explosives, the length of the ditch beyond the original charge was twice as great for the detonation end as it was at the end opposite detonation. No consistent difference was observed for these dimensions measured on Phase II ditches.

The greater depth and width of the ditch at the detonation end ("bulb" effect) was probably caused by the nonuniform confinement of the initial gaseous bubble. As the detonation wave front proceeds along the linear charge, the shock front is working against a free or unconfined region in one dimension. This is the region behind the detonation wave. The expanding gas bubble cannot maintain pressures as high as those which existed instantaneously at the time of detonation, since a part of the resulting pressure is permitted to escape into the unconfined region. Thus, the amount of material which is ejected from the ditch is somewhat less than that ejected at the location of initial detonation, and a lesser ditch depth and width result. It also appears reasonable to postulate that the unconfined region behind the propagating detonation wave would distort the particle trajectories of the ejected material. Subsequent trajectories would be directed upward and outward, but certainly not forward or in a direction along that of the detonation wave. There could even be a backward component in the ejected particle trajectory; i. e., a direction opposite to the direction of the detonation wave. Thus, fallback would not be found on the ground surface at the end opposite detonation.

Ditches resulting from multidetonation also exhibited certain detonation effects. Ditch C2a of Phase II was documented with high-speed motion photography. It was noted that the No. 2 and 3 detonators (in from the north end of the charge) appeared to be behind in their action with respect to the other detonators. An irregularity is noticeable in the outline of the resulting ditch. This is shown in the photographs of ditch C2a, Phase II, in Figure 17. It would appear that pressures built up in the vicinity of the two late detonators were actually less than pressures in other sectors of the charge. Thus, sufficient energy did not develop in that region to move as much material per foot of charge as was available along other sectors of the charge. Actual ditch volume in the vicinity of the late detonators was approximately 40 cubic feet per foot of charge. Farther south along the charge the volume was about 50 cubic feet per foot of charge.

A puzzling and interesting phenomenon observed during the Toboggan ditching series (and on other HE ditching experiments⁴) was the lack of fallback material on the ground surface at each end of the multidetonated linear charge craters. A photosonic camera was used to study the cloud at the south end of ditch C4a. Selected frames taken from the photosonic sequence are shown in Figure 18. A control point visible in each frame and the extreme outline of the cloud corresponding to each frame are also shown. Careful inspection of this photo-frame sequence reveals that the end portion of the cloud initially moving outward is drawn back into the main cloud at a later time (396 to 432 msec after detonation). This is probably due to the interaction of shock and rarefaction waves resulting in an interior low-pressure region in the dust cloud directly over the ditch. This region is probably most influential on the relatively low-pressure wave moving away from the end of the linear charge.

Figure 17. Multidetonation Effects on Resulting Ditch Outline

Figure 18. Photographic Sequence Showing Dust Cloud at South End of Ditch C4a

Distribution of the material ejected was unique in some respects for both Phase I and Phase II ditches. The highest concentration of fallback material is always found on the ground surface on either side of the longitudinal axis of the ditch, along a direction normal to it and to a significant distance removed from the ditch. For Phase I ditches there was some material found on the surface at the end of detonation. It was observed, for the deeply buried charges fired during Phase II, that a significant amount of throwout was deposited on the surface at the ends of the ditch (scaled depths of 2, 2.5, and 3).

Also of interest was the concentration of fallback noticeable after some of the larger shots. It appeared that large pieces of the medium remained intact throughout their flight and, to some degree, even during impact. However, the mounds which resulted lacked cohesiveness and would readily crumble if struck or kicked in their final position on the lakebed surface. Photographs of throwout distribution are shown in Figure 19.

Figure 19. Distribution of Throwout

(In upper photograph note throwout in each direction normal to longitudinal axis of an A-explosive ditch. Throwout is absent on surface at ditch ends. Note peculiar concentration of throwout for a C-explosive ditch in lower photograph.)

Crack Pattern

There was no definite program included in Toboggan for measuring ground surface cracks surrounding the ditches. Lawrence Radiation Laboratory representatives at the test site made such measurements. It is anticipated that a report covering this aspect will be issued.

It is interesting, however, to make a number of rather general observations concerning the crack pattern, using data that are available. A characteristic crack pattern was observed on the original ground surface surrounding each ditch. Absence of fallback over the original ground surface at the end opposite detonation for Phase I ditches permitted ready inspection of the resulting ground cracks. The pattern consisted of several close-in circumferential cracks, with radial cracks beyond. This sequence of cracks was observed to surround the entire ditch. Removal of fallback lip material was required in order that the crack pattern at locations other than at the end opposite detonation could be inspected. Figure 20 shows several examples of the crack pattern observed.

Circumferential cracks are not always parallel to the longitudinal edges of the apparent ditch. Although the explanation for this is probably complex, some theorizing seems to be appropriate. The circumferential crack zone represents a region stressed beyond its elastic limit, far into the plastic realm of behavior. The forces were radial. After the shock front had passed, soil in this zone rebounded to some extent. However, the varying degrees of stressing which had taken place in the plastic state prevented the same amount of rebound throughout. Thus, cracks were formed. Each crack can be associated with the location at which some given tensile stress occurred. The curved cracks indicate that tensile stresses were not the same intensity along a line parallel to the ditch edges. It is known that in a homogeneous medium a shock front will eventually become spherical at some distance even when it originates from a linear charge. Strength of the shock wave would be consistently constant along a line parallel to the ditch or axis of the linear charge only if the linear charge were infinite in length. It is possible that the curved cracks along the ditch edges are some manifestation of the tendency of the shock front to become spherical. Analogously, an eggshell-shaped shock front, changing with time to a sphere-shaped shell, can be visualized. It is realized, however, that the ground-surface-to-air boundary greatly complicates the way in which the shock front changes shape.

Permanent Displacement

The vertical component of permanent displacement along the original ground surface was measured for several ditches during Phase II of Toboggan. This measurement was made by setting spikes flush with the ground surface along lines normal to the ditch axes before firing the charge. All spikes were spaced at 1-foot intervals. Lines were oriented along the four major compass points. Displacements along a line normal to the longitudinal axis of the ditch are given in Table B-4 of Appendix B.

Permanent displacement measurements show the position of the true ditch lip. Figure 21 shows permanent ground displacement for the east and west lines on ditch C6a and the outline of the apparent ditch lip. Figure 22 shows the permanent surface displacement at each end of ditch C3a and B6b.

Figure 20. Surface Crack Pattern Resulting from Linear Charges

Figure 21. True and Apparent Lip for Ditch C6a

Figure 22. Permanent Ground Surface Displacements Along a Line Coincident with the Longitudinal Axis of Ditches B6b and C3a

Consider the sketch below:

Scaling considerations indicate that the vertical component of the permanent displacement along a line on the ground surface normal to the longitudinal ditch axis is related to the scaled distance from the linear charge by:

$$\frac{\Delta}{w^{1/2}} = f\left(\frac{X}{w^{1/2}}\right), \text{ or } \frac{\Delta}{X} = g\left(\frac{X}{w^{1/2}}\right),$$

where

Δ is the vertical component of permanent ground displacement measured at some distance from the charge,

X is the distance from the edge of charge to displaced point, and

w is the linear weight of chemical explosive.

The experimental data have shown that the relative displacement becomes

$$\frac{\Delta}{X} = k\left(\frac{X}{w^{1/2}}\right)^{\beta}.$$

This relationship is shown for the Toboggan C explosive in Figure 23 (data in Table B-3 Appendix B). Dimensionless displacement is plotted as a function of scaled distance from the charge. These data when fitted with a family of straight parallel lines have a slope of -4.2. (Actual and scaled displacement varies inversely as the scaled distance raised to the -3.2 power.) Also included in the illustration is a tabulation of displacement distance relationships for each scaled burst at which data were available.

Figure 23 indicates that permanent surface displacements are less when the charge is burst at a scaled depth of 0.50 than when it is burst at 0.25. At all other depths displacement increases with scaled burst depth. Inasmuch as a best fitted family of parallel lines is illustrated, rather than best fitted individual straight lines, caution must be exercised in drawing the conclusion that charges burst at a scaled depth of 0.25 actually give rise to greater surface displacements than do those burst at a scaled depth of 0.50. The statistical treatment given in Appendix C indicates that a parallel family of straight lines should probably not be used to fit these data.

Figure 23. Dimensionless Displacement as a Function of Scaled Distance from the Linear Charge

Charge Shape Effect

Explosive F was included in Project Toboggan to determine the effect of linear charge cross-sectional shape on ditch dimensions. This explosive had the same linear yield (10.8 pounds per foot) as explosive B. However, explosive F had a circular cross section 4.5 inches in diameter, whereas explosive B had a square cross section 4 inches by 4 inches. Figure 24 shows actual ditch width, depth, and volume for explosives B and F.

With the exception of data for surface burst depth, the F explosives appear to form larger ditches than do the B explosives. These apparent differences, based on average values at depths of burst of interest, are shown in the following tabulation:

Scaled Depth-of-Burst	Average width (ft)			Average depth (ft)			Average volume/ft (ft ³ /ft)		
	B	F	% F larger than B	B	F	% F larger than B	B	F	% F larger than B
1.0	14.5	16.2	11.6	3.9	4.2	7.8	1645	2185	32.8
2.0	20.2	22.1	9.5	4.2	5.2	22.4	4856	5814	19.9

The cross-sectional shape of the F and B charges are nearly the same. However, the tendency again appears for ditches from the F explosive to be slightly larger.

Effect of Backfill Procedure

The method of backfilling Toboggan trenches was a subject of much conjecture prior to the experiment. It was felt that the more nearly the backfill material approached the in situ condition the more valid would be test results. The ideal situation would entail burying a line charge and allowing the backfill to compact naturally over a rather long period of time. During Phase II of Toboggan the opportunity to observe such a naturally compacted ditch was presented. Ditch B4b was loaded and backfilled on January 8, 1960. However, before it could be fired, a heavy rain and snowstorm covered Yucca lake with water. Yucca lake bed conditions remained unfavorable for firing B4b until April 1st. Thus the charge was in the ground for almost three months. It would appear that sufficient time had elapsed to allow the backfill material to compact to the natural conditions of the surrounding medium. Ditch B4a, a shot similar to B4b with respect to burial depth and charge yield, was loaded and backfilled on April 17 and fired on April 18. Differences in ditch quantities caused by differences in backfill technique should be noticeable by comparison. The table below gives significant quantities for each ditch.

	Ditch width (ft)	Ditch depth (ft)	Volume (ft ³ /lb)
B4b	15.50	4.26	3.12
B4a	15.50	4.00	3.14

There appear to be no consistent differences in the above quantities.

Figure 24. Depth-of-Burst Plots Showing the Actual Relationship of Ditch Quantities for Explosives F and B

Charge Length Relative to Burst Depth

Other investigators have found that short linear charges which, when detonated on the surface to yield a ditch, must be significantly lengthened to create a ditch when burst below the surface. In other words, short linear charges may approach point charges when burst at certain depths below ground surface. It was decided for Project Toboggan that charges of sufficient length to create a ditch having parallel sides over at least the center third of the total ditch length should be used. Thus the ditching potential of linear charges used in Toboggan was evaluated on the basis of this center third of the ditch. To meet this requirement within economical limits, the charge lengths were varied directly with burst depth. No data were available for determining the charge length that would be required other than a few observations on former Sandia tests. Thus estimates of charge length were made and adjusted as indicated by Toboggan results. All Phase II ditches met the parallel edge requirement. Figure 25 gives the minimum length of charge required for each of the Toboggan explosives where a ditch having parallel sides along the center third of its length is to be produced. Curves presented in Figure 25 are not necessarily a plot of Toboggan data. Toboggan data in this instance have been modified to reflect the best estimate available after observation of Toboggan results. It should be emphasized that charge lengths taken from Figure 25 should yield ditches which are two-dimensional within their center one-third portion when burst in a Yucca Lake type of medium. Charge lengths which are approximately two-thirds or less of those given in Figure 25 would probably yield ditches having no two-dimensional region at the center.

Figure 25. Maximum Charge Length Required to Create Ditch Having Parallel Sides Along Center One-Third of its Total Length

Ditch Erosion

Of interest from a Plowshare standpoint is the weathering and water erosion to which the Phase I ditches were subjected. These ditches were exposed to several intense rainstorms and snowfalls during the winter months of 1960. Yucca lake was completely submerged during most of January and February. The peculiar distribution of throwout (end-detonated charges) permitted water to move freely into the ditches from the ends opposite detonation. To a degree, erosion resulted from water flowing into the ditches.

Longitudinal profiles and cross sections were run on several of the eroded ditches. It was possible, therefore, to determine the amount of material deposited along the ditch bottom and to observe the change that occurred to the ditch cross section. Table V gives significant data for each of the eroded ditches measured. Figure 26 shows before-and-after photographs of a typically eroded ditch, together with its profile and cross section.

TABLE V
Effects of Ditch Erosion

Ditch No. *	Length in feet			Width in feet			Depth in feet		
	Original	After erosion	Percent increase	Original	After erosion	Percent increase	Original	After erosion	Percent decrease
A1a	8.4	10.5	25	2.1	3.2	52	0.28	0.27	4
A3b	14.6	20.8	42	5.4	7.2	33	1.06	0.74	43
A4a	19.5	22.9	17	5.7	8.5	49	1.85	1.39	33
B3b	48.7	53.3	9	13.1	15.2	16	2.70	2.01	34
C1b	46.4	58.0	25	13.7	15.3	12	2.78	2.00	39
C1c	50.1	58.9	18	13.0	14.0	8	2.44	2.15	13
C2b	73.2	85.6	17	18.6	20.7	11	4.31	3.31	30

* Phase I

Ground Surface Motion over Linear Charge

Motion picture coverage was included for Phase II ditches C2a, C3a, and C4a. A half-frame 35-mm Fastax camera with a film speed of about 5000 frames per second was used for all three shots. In addition, a 35-mm Warrick with a film speed of 1400 frames per second was used for ditch C4a.

Resulting motion pictures indicated that the ground surface over charges C3a and C4a moved upward as a continuous mass during the very early time after detonation. Ditch C2a, Phase II, did not show a continuous mass motion over the charge (Figure 17).

Figure 27 shows ground surface movement directly over charges C3a and C4a during the first few milliseconds after detonation. Charge C3a, 75.3 feet long, was buried at a depth of 3.25 feet and contained 3160 pounds of TNT. Detonator locations were designated by 2-foot square targets placed directly over each detonator. The motion photos showed differential movement of the surface directly over the detonators and over the surface between the detonators. At about 9 milliseconds the ground surface mass had moved upward over 3 feet. Obviously tremendous velocities and accelerations were present during the very early times after detonation.

DITCH IMMEDIATELY AFTER DETONATION (12-7-1959)

DITCH AFTER SEVERAL MONTHS OF WEATHERING AND EROSION (4-15-60)

Figure 26. Erosion Characteristics of Ditch C2b

Figure 27. Ground Surface Movement Over Charges C3a and C4a

The Warrick and Fastax cameras give the same record for the surface motion over charge C4a. This charge, 100 feet long, was buried at 6.5 feet and contained 4200 pounds of TNT. (It should be noted that both charges, C3a and C4a, yielded 42.7 pounds of TNT per foot.) At about 38 milliseconds after detonation the ground surface had moved upward about 5 feet. As on C3a, detonator locations are obvious because of differential ground movement directly over the charge. However, this difference is not as pronounced as in C3a. In the case of charge C4a, the greater uniformity in ground movement along the charge and the longer time required for upward movement when these factors are compared to those affecting charge C3a are undoubtedly caused by the greater burial depth of C4a.

Ditch Cross Sections

Actual cross sections for A, B, C, and D ditches are illustrated in Figure 28. Also shown in a comparison of the cross sections from B and F charges. There is little difference in the B and F cross sections. However, the cross sections chosen to illustrate the F charges are slightly greater than those for the B charges where the charge is surface burst and burst at a scaled depth of 2.0.

The ditch formed from a charge detonated at a scaled burst depth of 1.5 exhibits the cross section with the greatest area for all Toboggan charges. Charges detonated at greater burial depths produce slightly wider ditches, but they are significantly more shallow. It is also interesting to note that the depth of the ditch is always less than the actual charge burial depth for scaled burst depths greater than 1.5.

Ditch Lip

All lip data obtained from Toboggan ditches are presented as Table B-6 in Appendix B. The following sketch shows the lip quantities tabulated.

Ditch Cross Section

Distance from the longitudinal axis of the ditch to the maximum apparent lip height, h_a , is L . Maximum measured true lip height is designated as h_t . An attempt at determining depth-of-burst functions and scaling relationships for the quantities h_a and h_t was not successful. The data scatter was such that apparent trends were imperceptible. The crude method of measuring true lip height probably accounts for the tremendous

Figure 28. Actual Cross Sections for Toboggan Ditches

scatter of these data. This is not true, however, for apparent lip height data. The author is at a loss to explain the great variations and lack of correlation for these data. Attempts to analyze other apparent lip height data have met with the same results.

The quantity, ℓ , when scaled and plotted as a function of depth of burst, yielded the plot shown in Figure 29. One would normally expect particle trajectory angles to depend on charge burst depth. Thus the final location of ejected material would be trajectory-dependent. The rather good correlation shown in Figure 28 is not surprising.

Figure 29. Distance from Center of Ditch to Maximum Lip Height as a Function of Depth of Burst

The distribution of the material ejected outward from the longitudinal axis of the ditch has been studied. Figure 30 presents the results for C explosive. On the graph distance from the ditch centerline is given in increments of ditch width. The ordinate shows the percentage of the total ejected material found on the surface between the outer line of interest and the ditch centerline. For example, Figure 30 shows that 40 percent of the total material ejected from a C explosive ditch was always found within one ditch width outward from the longitudinal axis of the ditch. It is also interesting to note that the charge buried at a scaled depth of 1.5 results in material ejected to the greatest distance. Similar plots for A, B, and D explosive showed the greatest distribution of ejected material for the charge buried at a scaled depth of 2.5.

Figure 30. Variation of Fallback Material Outward from Longitudinal Ditch Axis

Table VI shows the distribution of ejected material for each linear charge weight and scaled burial depth. The 100-percent limit is an approximation, inasmuch as it represents only the material measurable with a planimeter on a ditch cross-sectional drawing such as is shown in Figure 7. Measured in this manner, the values are accurate within +10 percent.

TABLE VI
Distribution of Ejected Material Given in Increments of Ditch Width
Measured Outward from Longitudinal Ditch Axis

		<u>A Ditches</u>						
Scaled burst depth	0.0	0.25	0.50	1.0	1.5	2.0	2.5	3.0
Limit of 50% of ejected material	---	0.9	1.3	1.0	1.0	1.0	1.4	1.0
Limit of 100% of ejected material*	---	1.2	2.5	1.6	2.2	1.8	3.0	1.8
		<u>B Ditches</u>						
Scaled burst depth	0.0	0.25	0.50	1.0	1.5	2.0	2.5	3.0
Limit of 50% of ejected material	0.7	0.9	1.0	1.0	1.1	0.9	1.1	1.3
Limit of 100% of ejected material*	1.4	2.1	1.8	1.7	2.3	1.5	3.0	3.5
		<u>C Ditches</u>						
Scaled burst depth	0.0	0.25	0.50	1.0	1.5	2.0	2.5	3.0
Limit of 50% of ejected material	0.8	0.9	0.8	0.9	1.2	0.9	0.9	0.9
Limit of 100% of ejected material*	0.9	1.8	1.6	2.6	3.0	1.7	2.2	1.6
		<u>D Ditches</u>						
Scaled burst depth	0.0	0.25	0.50	1.0	1.5	2.0	2.5	3.0
Limit of 50% of ejected material	1.2	1.3	0.8	1.0	1.0	1.1	1.6	0.9
Limit of 100% of ejected material*	2.1	2.1	1.4	1.7	2.7	3.0	3.7	1.5

* This is an approximate limit for 100% of the ejected material that could be measured from plotted ditch cross sections using a planimeter. Thus it includes the gross features of the throwout and ignores the thin layer dispersed to greater distances.

Influence of Medium Properties on Ditching

It has been determined that propagation of shock and pressure wave depends on medium strength properties of compression, shear, and tension, and also on medium density. Hino⁸ claims that compressive strength alone is responsible for the shape and peak pressure of shock waves propagated in rock. One can only speculate at this time as to the relative importance of medium strength properties with regard to their influence on medium fracture. Cook indicates that any relative motion which results in tension failure is the most important means of breaking rock.⁹ He also acknowledges, however, that shear fracture is also responsible for rock breakage.

It should be noted at this time, before the medium properties gathered for the Yucca material are examined, that the strength testing (triaxial tests) was done under static conditions. Rigorous analysis would require dynamic property information. Extensive testing of many materials has proven the significant differences that do exist between dynamic and static conditions.

The Yucca medium had a negligible tensile strength. It can be assumed, therefore, that its shearing strength would directly influence the ditch formed by a high-explosive charge. For solid bodies in contact, but having no adhesion or bond, the term friction is synonymous with the terms shearing strength and maximum shearing resistance. However, the Yucca Lake medium is a clay or a cohesive soil. This complicates the problem of determining its true shearing strength.

Taylor has outlined the factors which affect the shearing strength of clays:⁵

<u>Fundamental Factors Affecting Shearing Strength</u>	<u>Alternate and Interrelated Factors</u>
Friction angle	Pressure history
Intergranular pressure	Drainage conditions
Intermediate principal stress	Intrinsic pressure
Cohesion	Consolidation pressure
Structural strength	Apparent friction angles
Speed of shear	Void ratio
Colloidal phenomena	Water content
Degree of progressive action	Coulomb coefficient

A discussion of these factors is not within the scope of this report. Taylor's work (Chapter 15) gives such a discussion. It was not possible as part of the Toboggan program to investigate the medium thoroughly enough to evaluate each factor.

A consolidated, undrained shear test was conducted on the Yucca clay (see data, Appendix A). The procedure followed was as outlined by Lambe.¹⁰ This represented an attempt to obtain shear strength information on the specimen under confining pressure similar to those which existed in situ. Table VII gives apparent friction angle determined from triaxial tests. (A true friction angle could be obtained for a drained shear test; however, it is felt that such a test would not give a valid indication of the forces occurring during a dynamic or explosive test.) It appears that before significant correlations with the shear strength data can be made it is necessary to have dynamic stress.

TABLE VII

Apparent Friction Angles for Various Depths in Yucca Lake Soil

<u>Depth (feet)</u>	<u>Apparent friction angle (degrees)</u>	<u>Medium classification</u>
0.5	47	Clay
2.5	10	Clay
4.5	21	Clay
6.5	37	Sandy clay loam
10.5	1.2	Sand
14.5	46	Clay
17.5	35	Sandy clay loam
20.5	6	Sandy clay loam

Comparison of Row and Linear Charge Ditches

During the summer of 1959 several ditches were created on Yucca Lake by detonation of five rows of 8-pound charges and one row of 256-pound charges. Data for these ditches are given in Table B-7 of Appendix B and are plotted in Figure 31. In this illustration linear explosive equivalent yield for the row charge series is determined by dividing a single charge by the spacing between it and the adjoining single charge. Depth of burst is scaled by the square root of this equivalent linear yield.

Data shown in Figure 31 indicate that detonation of an equivalent amount of HE will result in ditches having similar dimensions, when spacing between charges is less than that at which separate contributions of individual charges become apparent. This is true for row charges described here and may be valid over the entire depth-of-burst range to those depths approaching containment. Although data for row charges are sparse for the Yucca Lake playa, those which exist indicate that no real efficiency advantage can be realized by either charge over the other.

Figure 31. Comparison of Ditches from Spaced Spherical and Linear Charges

CHAPTER VII -- CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions are drawn from an examination of all Toboggan data:

1. No significant departure from square-root scaling has been observed for ditch width and depth. Ditch volume scales directly as the linear charge weight.

2. The following empirical expressions can be used to relate ditch volume, width, and depth to scaled burst depth and HE linear charge yield:

$$\text{Volume} = (-1.1 \lambda_{\text{DOB}}^2 + 4.3 \lambda_{\text{DOB}} + 0.09) w^{1.0}$$

$$\text{Width} = (-0.83 \lambda_{\text{DOB}}^2 + 3.6 \lambda_{\text{DOB}} + 1.9) w^{0.53}$$

$$\text{Depth} = (-0.51 \lambda_{\text{DOB}}^2 + 1.5 \lambda_{\text{DOB}} + 0.25) w^{0.49}$$

(The inclusive limits for scaled burst depth are 0.0 to 3.0 for volume and width and 0.0 to 2.0 for depth.)

3. Optimum ditch width and depth occur at a scaled burst depth of about 2.2. Ditch depth is optimum at a scaled charge burst depth of about 1.5.

4. Assuming that depth-of-burst relationships established between unit spherical and unit linear charges hold for other media, the unit linear charge depth-of-burst relationship can be constructed solely from spherical charge crater data.

5. No significant differences were observed in either scaling or depth-of-burst plots for end-detonated and multidetonated linear charges.

6. These definite effects of end detonation were observed:

- (a) There was enlargement of the ditch at the detonation end of the charge.
- (b) No fallback debris on the ground surface at the charge end opposite detonation was observed.
- (c) Depression of the original ground surface was noted at the charge end opposite detonation.
- (d) A shorter ditch length extended beyond the charge at the end opposite detonation.

Such effects were absent when linear charges were multidetonated. Multipoint detonation resulted in little or no throwout opposite both ends of the charge.

7. Permanent displacement of the original ground surface varies inversely as the 3.2 power of the scaled distance from the charge. A definite depth-of-burst dependence of permanent ground displacement was observable for the Toboggan C explosive.

8. Charge cross-sectional shape may influence size of the resulting ditch. The circular charge (explosive F) appeared to create slightly larger ditch dimensions than did its equivalent explosive having a square cross section (explosive B).

9. The greatest areal ditch cross section results when charges are burst at a 1.5 scaled depth.

10. No significant deviation is apparent when spaced charges, reduced to their equivalent linear yield, are compared to depth-of-burst curves for linear charges.

11. Fifty percent of the measurable ejected material was found within 1.6 ditch widths outward from the longitudinal axis for all Toboggan ditches. All of the measurable throwout was found to be within 3.0 ditch widths for the A, B, and C charges, whereas this limit extended to 3.7 for the D charge.

Recommendations

It is recommended, for any Plowshare ditching application which utilizes HE line-charge equivalent of rows of nuclear explosives, that the scaled burst depth be within the range of 1.5 to 2.2. This scaled burst depth would be determined by dividing the actual burst depth by the square root of the equivalent nuclear linear yield.

One significant result of Toboggan was that, for the first time, dimensions of craters from line charges and point charges were obtained in the same medium. From these craters it has been possible to develop a relationship between craters from the two types of charges. If this relationship is the same for all media, an important contribution will have been made, since it would permit the deduction of line-charge crater dimensions from those of point-charge craters in any medium. Thus, it is essential that before the use of such a tool is attempted, the validity of the assumption that the relationship is the same must be tested. This is the most important recommendation for further work arising out of Project Toboggan.

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APPENDIX A
YUCCA DRY LAKE SOILS INVESTIGATION

The soils investigation at Yucca Dry Lake was conducted by Twining Laboratories of Long Beach, California. Samples were removed from a test pit on June 22, 1960. Data presented here are taken directly from the laboratory report.

Description of Soil Types Encountered (Figure A-1)

Depth (feet)

0 - 2.5	<u>Light brown to white silt.</u> This material is very dry and loose in its natural state. There is a distinct flaky characteristic apparent throughout the full depth of the material which results in a nonuniform mass containing many voids which, in turn, reduces the natural density of the material and introduces variations in strength and stability within the soil mass.
2.5 - 5.0	<u>Light brown to white silty clay.</u> This material is similar to that described above and displays the same flaky characteristic. However, due to the presence of clay particles, there are many cracks and fissures extending the full depth of the material which increases the variation of strength and stability within the soil mass. The cracks and fissures have developed from shrinkage of the clay upon drying.
6.5 - 7.75	<u>Brown sandy clay.</u> This is the same material as above, the only change being a slightly darker color.
7.75 - 13.0	<u>Brown very fine - coarse sand and gravel.</u> This material displays definite stratification in the upper two feet, but becomes more massive in the lower portion. The material is almost completely lacking in binder material and is friable under the slightest pressures. In addition, the individual particles are rounded to sub-rounded with very few angular faces. Most of the particles are hard; however, there is some evidence of weathering. As a result of the absence of binder material and the physical characteristics of the individual particles, the strength and stability of the soil mass is low.
13.0 - 15.0	<u>Reddish brown sandy clay.</u> This material appears to be in a semi-indurated condition. However, cracks and fissures in the material give it a blocky characteristic and introduce planes of weakness through the mass which result in variations of strength and stability.
15.0 - 18.75	<u>Light brown sandy clay.</u> This material also appears semi-indurated; however, the blocky characteristic described for the material from 13.0 to 15.0 feet is absent. Instead, there is a distinct platy characteristic which seems to follow bedding planes or sand partings within the soil mass. These planes are generally horizontal and do not have a great effect on the compressibility of the soil. They do affect, however, the shearing strength, causing it to vary throughout the mass.

- 18.75 - 19.25 Brown very fine - coarse sand and gravel. This material is identical to that encountered from 7.75 to 13.0 feet and displays the same characteristics.
- 19.25 - 20.5 Light brown sandy clay. This material is the same as that from 15.0 to 18.75 feet and displays the same characteristics. There may be a slightly higher sand content.

Figure A-1. Log of Test Boring

TABLE A-1

Moisture-Density Relationships

(Compaction Standard: ASTM Designation D698-58T, Methods of Test for Moisture-Density Relations of Soils, Using a 5.5 Rammer and 12-inch Drop (Method A)).

Depth of Sample (feet)	Material Type	Maximum Density (lbs/cu ft)	Optimum Moisture (percent)
0.5	Light tan-white clayey silt	100.5	22.5
4.5	Light tan-white silty clay	104.5	22.5
9.5	Brown fine-coarse sand	105.5	17.0
14.5	Reddish brown sandy clay	103.5	22.0
20.5	Light brown sandy clay	113.5	15.5

TABLE A-2

Field-Density Tests
ASTM Designation D1556-58T

(Method of Test for Density of Soil by the Sand Cone Method)

Test No.	Depth (feet)	Wet Density (lbs/cu ft)	Moisture (percent)	Dry Density (lbs/cu ft)	Maximum Density (lbs/cu ft)	Percent Maximum
1	20.5	67.4	9.9	61.4	113.5	54.1
2	17.5	77.8	13.0	68.8	113.5	60.6
3	14.5	90.3	19.8	75.5	103.5	72.9
4	10.5	79.9	8.1	73.8	105.5	70.0
5	6.5	82.7	10.5	75.0	104.5	71.9
6	4.5	64.4	8.7	59.3	104.5	56.8
7	2.5	70.5	13.6	62.1	100.5	61.8
8	0.5	69.3	12.4	61.6	100.5	61.3

TABLE A-3

Mechanical Analysis

(ASTM Designation D422-59T, Methods for Grain Size Analysis
of Soils and ASTM Designation D1140-54, Method of Test for
Amount of Material in Soils Finer than the No. 200 Sieve.)

Sample Depth (feet)	Maximum Size of Particles (millimeters)	Specific Gravity
0.5	0.02276	2.65
2.5	0.02700	2.47
4.5	0.02415	2.60
6.5	0.03060	2.47
9.5	0.03271	2.53
14.5	0.02595	2.60
17.5	0.03200	2.50
20.5	0.03101	2.55

Percent by Weight Passing
(sample depth in feet)

Screen Size	0.5	2.5	4.5	6.5	9.5	14.5	17.5	20.5
#4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
#8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
#10	100.0	100.0	100.0	100.0	95.65	100.0	100.0	100.0
#16	100.0	100.0	98.46	98.46	80.85	100.0	98.46	95.38
#30	98.46	98.46	96.92	93.84	46.05	98.46	90.76	84.59
#40	96.92	96.92	95.38	90.76	35.63	96.92	84.60	78.43
#50	95.38	95.38	93.84	87.68	30.41	95.38	78.44	72.27
#100	92.30	89.22	90.76	73.82	21.71	92.30	63.04	59.96
#200	89.22	79.98	84.60	58.42	17.23	86.14	47.64	50.72

Dispersing Agent

The dispersing agent used in the hydrometer analysis portion of this test was prepared by mixing 42.5 gms of sodium hexametaphosphate (Calgon) with 1 liter of distilled water.

Refer to Figure A-2 for graphical results of hydrometer analyses and sieve analyses.

TABLE A-4
Hydrometer Analysis
(ASTM Designation D1140-54)

<u>Sample Depth (feet)</u>	<u>Percent Finer Than No. 200 Sieve</u>
0.5	96.2
2.5	77.2
4.5	91.6
6.5	62.8
9.5	6.0
14.5	92.0
17.5	67.4
20.5	64.4

Consolidation Tests

Consolidation tests were performed on undisturbed samples of the soil types at their natural moisture contents, and were run to determine maximum preconsolidation pressure (natural vertical state of stress or maximum consolidation pressure). The samples were tested in fixed ring, beam-loaded consolidometers, following the procedure outlined below:

- a. Trim the specimen to insure as near a perfect fit as possible.
- b. Place the specimen in the loading unit.
- c. Set a vertical deflection dial on the holder.
- d. Apply the load to give a pressure intensity of 1/4 ton per square foot on the soil specimen, and start taking time and vertical deflection readings. Continue readings at half-hour intervals.
- e. Increase the load on the specimens to 1/2 ton per square foot when two successive dial readings at the half-hour intervals indicate less than 0.01 percent consolidation.
- f. Continue to load the specimen by doubling the previous load as described in subparagraph e above.
- g. Plot consolidation versus load pressure on a semilog graph paper and determine maximum precompression pressure by the tangent method.

Refer to Figure A-3 for graphical results of the consolidation tests, with settlement in inches per inch plotted arithmetically against unit loads.

Figure A-4 shows settlement versus time for individual load increments. The void-ratio-versus-pressure plots used in determination of maximum precompression pressures are given in Figure A-5.

SAMPLE DEPTH = 0.5'

SAMPLE DEPTH = 2.5'

SAMPLE DEPTH = 4.5'

SAMPLE DEPTH = 6.5'

SAMPLE DEPTH = 10.5'

SAMPLE DEPTH = 14.5'

SAMPLE DEPTH = 17.5'

SAMPLE DEPTH = 20.5'

Figure A-2. Graphical Results of Hydrometer and Sieve Analysis for Yucca Dry Lake Soil

Figure A-3. Settlement Plotted Versus Unit Loads

Figure A-4. Settlement Versus Time for Individual Load Increments

Figure A-5. Void Ratio Versus Pressure

Triaxial Compression Tests

Triaxial compression tests were performed on undisturbed samples of the soil types at their natural moisture contents.

The test was conducted in accordance with the procedure for triaxial compression tests on cohesive soils.¹⁰ The samples were preconsolidated to 60 percent of the maximum precompression pressure as determined from the consolidation tests for one hour or until no further change in length of the specimen was observed. After preconsolidation, each of the three samples from the same depth was tested at a different lateral pressure. The samples were tested at field moisture content and loaded at a uniform strain rate of 0.05 inch per minute.

Refer to Figure A-6 for results of the triaxial compression tests.

Figure A-6. Triaxial Compression Results

APPENDIX B
DATA TABLES FOR ALL TOBOGGAN DITCHES

TABLE B-1

Data Log for Linear-Charge Ditches, Phase I

Ditch	Date (1959)	Winds		Explosive length (ft)	Total explosive weight (lbs)	Depth of burst (ft)	Average ditch width (ft)	Average ditch depth (ft)	Volume of ditch (cu ft)
		Velocity (mph)	Direction (degrees)						
Explosive A									
A1a	10-30	20	005	7.5	13	0	2.14	0.27	2.93
A1b	10-31	20	025	7.5	13	0	1.90	0.35	3.36
A1c	10-31	20	025	7.5	13	0	2.17	0.33	3.51
A2a	10-31	11	045	9.4	17	0.33	3.53	0.92	16.51
A2b	11-1	14	055	9.4	17	0.33	4.20	1.15	24.38
A2c	11-1	14	055	9.4	17	0.33	4.52	0.78	20.26
A3a	11-1	8	105	11.3	20.5	0.65	4.79	1.14	37.23
A3b	11-1	8	105	11.1	20.0	0.65	5.35	1.04	39.88
A3c	11-3	0.5	120	11.3	20.5	0.65	4.70	1.10	34.86
A4a	11-16	0.5	110	15.0	27.0	1.31	6.27	1.89	88.14
A4b	11-18	5	0	15.5	28.0	1.31	6.67	1.63	97.28
A4c	11-19	5	0	15.2	27.5	1.31	5.66	1.89	103.5
A5a	11-19	5	150	18.5	33.5	1.97	6.35	2.21	139.1
A5b	11-21	5	080	18.8	34.0	1.97	7.46	2.40	169.2
A5c	11-21	5	080	18.8	34.0	1.97	7.43	2.12	157.4
A6a	11-16	0.5	110	22.9	41.5	2.62	4.39	2.26	262.8
A6b	11-20	5	150	26.5	48.0	2.62	6.30	1.42	224.2
A6c	11-20	5	150	26.8	48.5	2.62	7.10	1.47	230.0
Explosive B									
B1a	11-3	0.5	120	19.3	208	0	5.90	1.19	73.56
B1b	11-3	20	190	18.5	198	0	6.33	1.23	74.00
B1c	11-4	20	360	18.5	198	0	6.04	1.30	72.71
B2a	11-4	20	360	23.8	257	0.82	8.52	1.68	175.6
B2b	11-5	10	050	23.8	257	0.82	10.52	2.22	276.6
B2c	11-9	3	105	29.4	317	0.82	9.08	1.96	271.2
B3a	11-10	4	160	38.6	416	1.64	11.55	3.09	812.7
B3b	11-11	0.7	105	38.6	416	1.64	10.96	2.82	611.1
B3c	11-11	9	165	38.6	416	1.64	11.93	2.60	805.6
B4a	11-18	0.5	150	53.1	574	3.28	12.60	3.32	1410.0
Explosive C									
C1a	11-12	12	160	38.9	1640	0	12.74	2.10	635.0
C1b	11-12	0.5	180	38.9	1640	0	11.82	2.78	615.9
C1c	12-2	0.5	180	42.6	1800	0	12.51	2.31	702.3
C2a	12-7	0	---	60.0	2517	1.65	19.16	3.55	2391
C2b	12-7	0	---	60.0	2517	1.65	17.18	4.30	2434
C2c	12-9	0	---	60.0	2517	1.65	21.03	3.41	2730
C3a	12-11	0	---	75.0	3157	3.30	28.52	4.05	7608
C3c	12-15	0.5	315	75.0	3157	3.30	30.67	5.20	8628
Explosive D									
D1a	12-12	0	---	4	0.92	0	0.90	0.15	0.30
D1b	12-12	0	---	4	0.92	0	0.90	0.17	0.32
D2a	12-12	0	---	6	1.38	0.12	0.74	0.31	1.36
D2b	12-12	0	---	6	1.38	0.12	1.28	0.32	1.59
D3a	12-12	0	---	8	1.84	0.24	1.98	0.45	4.05
D3b	12-12	0	---	8	1.84	0.24	1.80	0.50	3.93

TABLE B-1 (cont)

Crater	Date (1959)	Winds		Depth of burst (ft)	Average crater diameter (ft)	Average crater depth (ft)	Volume of charge (cu ft)
		Velocity (mph)	Direction (degrees)				
Data Log for 8-Pound Single-Charge Craters							
E1a	11-23	18	030	0	3.10	0.91	2.33
E1b	11-23	18	030	0	2.94	0.67	1.76
E1c	11-24	0.5	315	0	2.62	0.65	1.54
E2a	11-24	0.5	315	0.5	5.09	1.11	11.55
E2b	11-24	0.5	090	0.5	4.50	1.06	8.00
E2c	11-24	0.5	090	0.5	4.86	1.44	11.56
E3a	11-24	0.5	090	1.0	5.56	1.60	15.69
*E3.5a	6-16-60	0	---	1.5	5.70	1.71	18.1
E3b	11-24	0.5	090	1.0	6.04	1.54	17.03
E3c	11-24	0.5	090	1.0	5.40	1.75	15.68
E4a	11-24	0.5	090	2.0	6.86	1.77	26.64
*E4.5a	6-18-60	0	---	2.5	7.50	1.48	27.4
E4b	11-24	0.5	090	2.0	7.12	1.94	34.32
*E4.5b	6-18-60	0	---	2.5	6.62	1.01	13.0
E4c	11-24	0.5	090	2.0	7.35	1.81	36.37
E5a	11-14	16	360	3.0	7.36	0.80	16.82
*E5.5a	6-18-60	0	---	3.5	6.32	0.34	7.05
E5b	11-15	7	315	3.0	8.00	1.79	38.70
E5c	11-15	7	315	3.0	7.32	0.67	13.72
E6a	11-15	7	315	4.0	3.81	0.20	1.24
*E6.5a	6-18-60	0	---	4.5	0	0	0
E6b	11-15	7	315	4.0	3.00	0.12	0.52
E6c	11-15	7	315	4.0	4.80	0.11	2.22
*E7a	6-18-60	0	---	5.0	0	0	0

* Shot during Phase II

TABLE B-2
Data Log for Linear-Charge Ditches, Phase II

Ditch	Date (1960)	Winds		Explosive length (ft)	Total explosive weight (lbs)	Depth of burst (ft)	Average ditch width (ft)	Average ditch depth (ft)	Volume of ditch (cu ft)
		Velocity (mph)	Direction (degrees)						
Explosive A									
A1a	12-15*	0	---	12.0	21.8	0.0	1.7	0.20	3.25
A2a	4-2	12	N	14.7	27.5	0.33	3.72	0.74	19.20
A3a	4-13	0	---	20.0	37.0	0.65	3.87	0.79	27.5
A4a	5-6	0	---	30.2	55.0	1.34	6.04	1.63	156.0
A5a	5-10	0	---	40.1	73.0	2.04	6.78	1.79	227.2
A6a	5-11	3	SW	50.0	91.0	2.67	7.18	1.51	356
A7a	5-13	5	N	60.2	108.5	3.36	6.78	0.89	280
A8a	5-16	3	N	70.3	128.0	4.02	NA	NA	125
Explosive B									
B1a	6-17	10	SW	25.4	267.0	0.0	6.00	1.30	89.1
B1b	12-15*	0	---	25.4	267.0	0.0	5.49	1.14	74.0
B2a	4-4	3	NE	34.6	363.8	0.81	7.65	2.00	230
B2b	4-4	5	NE	34.6	363.8	0.83	9.45	2.60	347
B3a	4-13	0	---	41.6	436.2	1.64	11.60	2.50	632
B3b	4-12	15	340	41.9	436.2	1.64	11.70	2.80	759
B4a	4-18	10	180	53.6	563.9	3.27	15.50	4.00	1768
B4b	4-1	15	0	52.1	565.2	3.27	15.50	4.26	1762
B5a	4-19	10	90	67.9	712.9	4.90	18.70	4.89	3540
B5b	4-21	10	90	67.0	702.2	4.90	18.40	4.66	3312
B6a	4-20	0	---	82.0	861.8	6.54	19.39	3.95	4437
B6b	4-20	10	---	81.3	851.2	6.54	21.03	4.50	5275
B7a	4-29	15	0	95.2	1003.9	8.19	21.18	4.00	5580
B7b	5-3	13	S	95.2	1014.6	8.22	22.11	5.07	7560
B8a	5-27	0	---	111.3	1170.4	9.80	19.40	3.58	4600
B8b	6-16	10	S	111.6	1170.4	9.70	16.40	2.96	4550
Explosive C									
C1a	12-15*	0	---	45.0	1920	0.0	11.94	2.30	598
C2a	4-7	12	SW	60.0	2519	1.62	19.70	4.33	2962
C3a	4-8	0	---	75.3	3160	3.25	26.49	5.30	6150
C4a	6-9	0	---	100.9	4223	6.50	29.6	7.83	14300
C5a	6-9	0	---	125.0	5240	9.75	39.4	11.4	30000
C6a	6-7	0	---	151.5	6356	13.10	38.3	7.34	33600
C7a	6-7	0	---	177.1	7423	16.50	41.1	6.62	29300
C8a	6-22	10	SW	201.3	8447	19.92	32.8	6.27	26000
Explosive D									
D1a	12-15*	0	---	4.0	0.92	0.0	0.90	0.13	0.38
D1b	12-15*	0	---	4.0	0.92	0.0	1.70	0.18	0.43
D2a	4-2	0	---	6.0	1.38	0.12	1.50	0.28	1.35
D2b	4-2	0	---	6.0	1.38	0.12	1.45	0.28	1.16
D3a	4-13	0	---	8.0	1.84	0.24	1.69	0.36	3.06
D3b	4-13	0	---	8.0	1.84	0.24	1.87	0.39	3.51
D4a	5-5	3	NE	10.0	2.30	0.48	2.58	0.56	9.60
D4b	5-6	0	---	10.0	2.30	0.48	2.85	0.76	8.25

* 1959

TABLE B-2 (cont)

Ditch	Date (1960)	Winds		Explosive length (ft)	Total explosive weight (lbs)	Depth of burst (ft)	Average ditch width (ft)	Average ditch depth (ft)	Volume of ditch (cu ft)
		Velocity (mph)	Direction (degrees)						
Explosive D (cont)									
D5a	5-6	0	---	11.8	2.76	0.72	2.80	0.74	11.44
D5b	5-6	0	---	12.1	2.76	0.72	2.50	0.71	7.52
D6a	5-7	0	---	15.0	3.45	0.96	2.80	0.56	17.5
D6b	5-7	0	---	15.0	3.45	0.97	2.88	0.52	20.2
D7a	5-9	0	---	17.0	3.91	1.20	2.26	0.35	15.8
D7b	5-9	0	---	17.0	3.91	1.20	2.33	0.27	13.9
D8a	5-13	0	---	19.0	4.37	1.44	3.10	0.38	22.4
D8b	5-13	0	---	19.0	4.37	1.45	2.45	0.03	8.4
Explosive F									
F1a	5-19	10	N	26.0	283.4	0	5.53	1.00	72.8
F1b	5-20	0	---	26.0	283.4	0	6.48	1.18	82.4
F1c	5-20	5	SW	26.0	283.4	0	6.37	0.99	83.2
F4a	5-25	0	---	54.0	591.6	3.26	16.40	3.90	2196
F4b	6-1	15	N	53.8	591.6	3.28	14.85	4.25	1917
F4c	5-31	10	S	54.0	591.6	3.27	17.42	4.31	2448
F6a	6-16	0	---	80.12	872	6.64	22.5	5.48	5900
F6b	6-3	12	N	80.04	872	6.55	21.75	4.88	5737

TABLE B-3

Ground Surface Permanent Displacement Normal to Longitudinal Ditch Axis
(feet)

Dist from C. of Ditch (feet)	A7a		B5b		B6b		B7a		B7b		F4a		C2a		C3a		C4a		C5a		C6a		C7a		C8a	
	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W
0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	0.018	0.030	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	-0.015	0.015	0.446	0.550	0.157	0.69	-	-	-	-	-	0.151	1.91	1.53	-	-	-	-	-	-	-	-	-	-	-	-
20	0.012	0.015	0.156	0.242	0.346	0.30	0.330	0.325	0.280	0.49	0.50	0.045	0.68	0.41	-	-	1.53	2.14	-	-	-	-	-	-	-	3.76
25	0.015	0.015	0.076	0.055	0.257	0.13	0.155	0.215	0.147	0.27	0.030	0.020	0.50	0.15	0.405	0.375	0.77	0.60	-	-	-	-	-	-	-	3.06
30	0.010	0.015	0.043	0.032	0.009	0.11	0.110	0.120	0.105	0.13	0.020	0.010	0.15	0.18	0.195	0.260	0.35	0.21	1.11	0.530	1.06	1.05	-	0.89	-	2.01
35	0.010	0.015	0.030	0.030	0.043	0.06	0.073	0.077	0.057	0.08	0.013	0.000	0.10	0.26	0.076	0.170	0.13	0.14	0.61	0.200	0.50	0.28	-	0.63	-	1.30
40	0.012	0.013	0.025	0.028	0.010	0.02	0.068	0.060	0.030	0.05	0.013	0.000	0.10	0.16	0.006	0.035	0.09	0.10	0.35	0.130	0.25	0.10	-	0.52	-	0.93
45	0.015	0.015	0.020	0.045	0.017	0.02	0.040	0.035	0.030	0.04	0.017	0.000	0.04	0.06	0.030	0.025	0.05	0.06	0.20	0.085	0.17	0.05	-	0.38	-	0.40
50	0.008	0.010	0.020	0.035	0.010	0.02	0.080	0.030	0.030	0.02	0.015	-0.010	0.04	0.05	0.015	0.020	0.05	0.06	0.12	0.060	0.21	0.04	-	0.31	-	0.29
55	0.005	0.010	0.020	0.034	0.000	0.01	0.029	0.023	0.025	0.02	0.015	0.010	0.03	0.05	0.015	0.010	0.05	0.06	0.07	0.083	0.26	0.07	-	0.23	-	0.23
60	0.010	0.008	0.012	0.025	0.005	0.01	0.015	0.025	0.010	0.01	0.015	0.005	0.03	0.04	0.022	0.007	0.05	0.05	0.04	0.110	0.19	0.05	-	0.17	-	0.20
65	0.005	0.005	0.015	0.015	0.000	-0.01	-0.005	0.010	0.012	0.01	0.012	0.005	0.02	0.03	0.003	0.010	0.03	0.03	0.03	0.080	0.06	0.02	-	0.13	-	0.13
70	0.002	0.004	0.007	0.013	0.000	0.00	0.005	0.010	0.005	0.01	0.010	0.000	0.01	0.02	0.003	0.000	0.02	0.03	0.02	0.076	0.03	0.03	-	0.10	-	0.05
75	0.000	0.001	0.005	0.010	-0.005	0.00	-0.001	0.000	0.010	0.01	0.008	-0.003	0.01	-	0.020	-	0.03	0.01	0.04	0.049	0.03	0.05	-	0.08	-	0.06
80	-0.005	0.005	0.005	0.006	-0.005	0.00	0.010	0.015	0.005	0.00	0.010	0.000	-	-	-	-	0.03	0.01	0.06	0.040	0.04	0.03	-	0.04	-	0.08
85	0.000	0.000	0.006	0.010	-0.015	0.00	0.003	0.007	0.005	0.00	0.008	-0.005	-	-	-	-	0.02	0.01	0.03	0.025	0.04	0.02	-	0.04	-	0.05
90	0.000	0.005	0.005	0.010	-0.020	0.00	0.000	0.008	0.000	0.00	0.005	-0.005	-	-	-	-	0.01	0.01	0.03	0.030	0.03	0.01	-	0.02	-	0.03
95	0.000	0.005	0.005	0.010	-0.029	0.00	-0.009	0.008	0.000	0.00	0.000	-0.005	-	-	-	-	0.01	0.02	0.02	0.025	0.03	0.01	-	0.02	-	0.02
100	0.005	0.005	-	-	-0.015	0.00	-0.005	0.005	-0.005	0.00	0.008	-0.010	-	-	-	-	0.01	0.01	0.02	0.025	0.01	0.00	-	0.01	-	0.02
105	-	-	-	-	-0.020	0.00	-0.010	0.000	-0.005	-0.01	0.000	-0.015	-	-	-	-	0.01	0.01	0.01	0.025	0.01	0.00	-	0.01	-	0.02
110	-	-	-	-	-0.020	0.00	-0.010	0.000	-0.005	0.00	0.000	-0.005	-	-	-	-	0.01	0.01	0.02	0.020	0.01	0.00	-	0.02	-	0.02
115	-	-	-	-	-0.015	0.00	-0.010	0.000	-0.010	0.00	0.000	-0.005	-	-	-	-	0.01	0.00	0.02	0.030	0.00	0.00	-	0.00	-	0.02
120	-	-	-	-	-0.025	0.00	-0.010	-0.005	-0.010	0.00	0.000	-0.010	-	-	-	-	0.01	0.00	0.01	0.020	0.00	0.00	-	0.01	-	0.02
125	-	-	-	-	-0.020	-0.01	-0.010	0.000	-0.010	0.00	-0.005	-0.015	-	-	-	-	0.01	0.00	0.01	0.015	0.00	0.00	-	0.00	-	0.02
130	-	-	-	-	-0.025	-0.01	-0.010	0.000	-0.005	0.00	0.000	-0.010	-	-	-	-	0.01	-0.01	0.00	0.020	0.01	0.01	-	0.00	-	0.02
135	-	-	-	-	-0.020	-0.01	-0.010	-0.004	-0.005	-0.01	0.000	-0.015	-	-	-	-	0.01	-0.01	0.01	0.015	0.02	0.00	-	0.00	-	0.01

NOTE: Negative displacements are downward.

TABLE B-4

**Toboggan Permanent Displacement Coincident with Longitudinal Ditch Axis
(feet)**

Distance from End of Trench (feet)	A7a		B5b		B6b		B7a		B7b		C3a		C4a		C5a		C6a		C7a		F4a	
	N	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S
2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-0.035	0.085	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	0	0.005	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	0.010	0	-0.085	-0.240	-0.040	-0.490	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.030	-0.050
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	0.010	0.215	0.035	-	0.015	-0.010	-	-	-	-	-0.245	-0.305	-	-	-	-	-	-	-	-	0	-
11	-	-	-	-	-	-	-	-	-	-	-0.200	-0.185	-	-	-	-	-	-	-	-	-	-
12	0	0	0.025	0.093	0.010	-0.010	-0.015	-	-0.200	0.025	-0.045	-0.040	0.010	-	-	-	-	-	-	-	0	-
13	-	-	-	-	-	-	-	-	-	-	0.010	0.020	-	-	-	-	-	-	-	-	-	-
14	0.005	0	0.015	0.035	0.015	0.010	0.010	0.005	0.015	0.010	0.010	0.015	0.080	0.060	0.140	-	-	-	-	-	0	-
15	-	-	-	-	-	-	-	-	-	-	0.010	0.005	-	-	-	-	-	-	-	-	-	-
16	0	0	0.015	0.010	0.005	0.010	-0.005	0.040	0.005	0.005	0	0	0.030	0.030	0.115	0.105	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-	-	-	0.020	0.005	-	-	-	-	-	-	-	-	-	-
18	0	0	0.015	0.015	-0.005	0.020	0.005	-0.005	0	0.005	0.005	0	0.020	0.020	0.060	0.045	-	0.170	-	-	0.005	-
19	-	-	-	-	-	-	-	-	-	-	0	0	-	-	-	-	-	-	-	-	-	-
20	0.005	0	0.020	0.015	0	0.015	0.005	0.015	0.010	0.010	0	0	0.020	0.020	0.040	0.035	0.035	0.130	-	-	0	-
21	-	-	-	-	-	-	-	-	-	-	0.010	-0.005	-	-	-	-	-	-	-	-	-	-
22	0	0.005	0.015	0.015	0	0.015	0.010	0.010	0.005	0.010	0.005	-0.005	0.020	0.020	0.035	0.025	-0.005	0.050	-0.050	-	0	-
23	-	-	-	-	-	-	-	-	-	-	0.005	-0.010	-	-	-	-	-	-	-	-	-	-
24	0	0.005	0.010	0.020	0	0	0	0.010	0.005	0.010	0.005	0	0.015	0.020	0.035	0.030	0.025	0.035	-0.035	-	0.005	-
25	-	-	-	-	-	-	-	-	-	-	0	-0.005	-	-	-	-	-	-	-	-	-	-
26	0	0	0.015	0.015	0	-0.010	0	0.010	0.005	0.005	-0.005	-0.010	0.010	0.015	0.025	0.030	0.020	0.035	-0.010	-	0	-
27	-	-	-	-	-	-	-	-	-	-	-0.005	-0.005	-	-	-	-	-	-	-	-	-	-
28	0	0	0.010	0.010	0.010	0.005	0	0.005	0.005	0.005	-0.005	-0.005	0.010	0.015	0.025	0.020	0.010	0.030	-0.010	-	0	-
29	-	-	-	-	-	-	-	-	-	-	0	0	-	-	-	-	-	-	-	-	-	-
30	0	0	0.015	0.015	-0.005	0.005	0	0.010	0.005	0	0	-0.005	0.010	0.020	0.020	0.025	-0.010	0.025	-0.010	-	0	-
31	-	-	-	-	-	-	-	-	-	-	0	-0.005	-	-	-	-	-	-	-	-	-	-
32	-	0	0.015	0.010	-0.010	-0.010	0.010	0	0.005	-0.005	0	-0.005	0.015	0.015	0.020	0.025	-0.010	0.030	-0.010	-	0	-
33	-	-	-	-	-	-	-	-	-	-	0	-0.005	-	-	-	-	-	-	-	-	-	-
34	-	0	0.015	0.015	-0.005	-0.005	0.010	0.005	0	0	0	-0.005	0.010	0.020	0.020	0.025	-0.005	0.025	-0.030	-	0	-
35	-	-	-	-	-	-	-	-	-	-	0.005	-0.005	-	-	-	-	-	-	-	-	-	-
36	-	0	0.020	0.010	-0.005	0	0	0.010	0	0	0	-0.005	0.010	0.015	0.025	0.020	0	0.020	-0.015	-	0	-
37	-	-	-	-	-	-	-	-	-	-	0.005	0	-	-	-	-	-	-	-	-	-	-
38	-	0	0.010	0.010	0.035	0	0	0.010	0.005	0	0	0	0.010	0.020	0.025	0.015	0	0.020	0	-	-	-
39	-	-	-	-	-	-	-	-	-	-	0.005	0	-	-	-	-	-	-	-	-	-	-
40	0	0.005	0.010	-	-0.005	-0.005	-0.015	0.005	0.005	0.005	0.005	0	0.010	0.020	0.025	0.015	0	0.020	-0.015	-	-	-
41	-	-	-	-	-	-	-	-	-	-	0	0	-	-	-	-	-	-	-	-	-	-
42	-	0	0.010	-	-0.010	-0.005	0	-0.005	-0.005	-	0	-0.005	0.010	0.020	0.025	0.015	0	0.020	0.005	-	-	-
43	-	-	-	-	-	-	-	-	-	-	0.005	-0.005	-	-	-	-	-	-	-	-	-	-
44	-	0	0.015	0.005	-0.005	-0.005	0	0.010	-0.005	-	0	-0.010	0.010	0.015	0.025	0.020	0	0.015	0	-	-	-
45	-	-	-	-	-	-	-	-	-	-	0.005	-0.005	-	-	-	-	-	-	-	-	-	-
46	-	0	0.015	-	-0.010	-0.005	-0.005	0.005	0	-	0.005	-0.005	0.010	0.015	0.025	0.020	-0.005	0.015	0	-	-	-
47	-	-	-	-	-	-	-	-	-	-	0	-0.010	-	-	-	-	-	-	-	-	-	-
48	-	0.005	0.010	-	-0.010	-0.005	0	0	-0.010	-	0.010	-0.010	0.005	0.015	0.020	0.020	0	0.015	-0.005	-	-	-
49	-	-	-	-	-	-	-	-	-	-	0.005	-0.005	-	-	-	-	-	-	-	-	-	-
50	0	0	0.020	0.015	-0.010	-0.010	0	0	-0.005	-	0	-0.010	0.005	0.020	0.020	0.020	0.005	0.015	0	-	-	-
51	-	-	-	-	-	-	-	-	-	-	0.005	-0.015	-	-	-	-	-	-	-	-	-	-
52	-	-	-	-	-	-	-	-	-	-	0	-0.020	-	-	-	-	-	-	-	-	-	-
53	-	-	-	-	-	-	-	-	-	-	0	-0.015	-	-	-	-	-	-	-	-	-	-
54	-	-	-	-	-	-	-	-	-	-	0.005	-0.015	-	-	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-0.005	0	-0.010	-	0	-0.010	0.005	0.015	0.025	0.020	0	0.015	-0.005	-	-	-
60	-	-	-	-	-	-	-0.005	0	-0.010	-	-	-	0.010	0.020	0.025	0.020	0	0.020	-0.010	-	-	-
65	-	-	-	-	-	-	-0.005	0.005	-0.005	-	-	-	0.005	0.015	0.025	0.015	0	0.010	-0.005	-	-	-
70	-	-	-	-	-	-	-0.005	0.010	-0.005	-	-	-	0.010	0.010	0.020	0	0.005	0.015	-0.010	-	-	-
75	-	-	-	-	-	-	-0.005	0.005	-0.010	-	-	-	0.005	0.010	0.020	0.010	0.005	0	-	-	-	-

NOTE: Negative displacements are downward.

TABLE B-5

Density and Moisture Content for Trench Backfill

Date	Location	Wet density (lbs/ft ³)	Dry density (lbs/ft ³)	Moisture content (percent)
11/59	A6a* at surface	97.1	82.4	18.0
11/59	A4b* at surface	81.5	70.2	16.1
11/59	C3a* at depth of 4 ft	--	85.2	9.8
4/22/60	B6a	81.7	74.3	10.0
4/20/60	B5b	84.8	80.0	6.0
4/28/60	C2a	95.1	81.4	17.4
4/29/60	B7a, N. end	74.4	67.7	10.0
4/29/60	B7a, S. end	87.6	82.4	6.3
5/19/60	C5a	100.5	88.3	14.0
5/26/60	C6a	75.0	64.7	16.0
6/17/60	C8a	91.5	75.0	22.0

* Phase I ditches

TABLE B-7

Data Log for Ditches from Spaced Charges

Ditch No.	Charge Configuration			Yield per ft (lbs)	Depth of burst (ft)	Average ditch width (ft)	Average ditch depth (ft)	Ditch volume (ft ³)
	No.	Weight (lbs)	Space (ft)					
A1	6	8	3.0	2.66	2.0	10.0	2.04	179.0
B2	6	8	3.5	2.29	2.0	7.09	2.01	187.0
C3	6	8	4.0	2.0	2.0	7.00	1.65	160.2
D4	6	256	12.7	20.16	6.34	23.01	5.21	5507.0
E5	6	8	5.0	1.60	2.0	5.8	2.04	153.0
F6	6	8	6.0	1.33	2.0	6.48	1.41	1 charge misfired

TABLE B-6

Toboggan Ditch Lip Data
(Phase II data only)

Shot	Max. height of apparent lip h _a (ft)	Max. height of true lip h _t (ft)	Distance to Max. apparent lip L (ft)
A2a	0.2	-*	2.8
A3a	0.4	-	3.2
A4a	0.7	-	4.6
A5a	0.8	-	6.0
A6a	2.1	-	6.3
A7a	1.0	0.033	6.2
A8a	0.7	-	6.2
B1a	0.5	-	5.2
B1b	0.3	-	4.0
B2a	0.9	-	6.3
B2b	1.2	-	6.1
B3a	1.4	-	8.6
B3b	1.3	-	8.8
B4a	2.1	-	10.1
B4b	1.5	-	10.8
B5a	2.0	-	13.1
B5b	2.2	0.50	12.2
B6a	2.9	-	13.4
B6b	2.7	0.56	14.4
B7a	2.0	0.50	13.7
B7b	3.0	0.60	15.0
B8a	1.8	-	16.2
B8b	2.4	-	14.1
C1a	1.7	-	8.8
C2a	2.5	1.72	14.1
C3a	3.0	0.68	17.9
C4a	2.5	2.25	19.9
C5a	2.8	0.90	25.0
C6a	3.5	1.21	27.9
C7a	5.7	1.46	28.9
C8a	5.6	3.76	38.5
D1b	0.06	-	1.2
D2a	0.07	-	1.0
D2b	0.07	-	1.0
D3a	0.11	-	1.2
D3b	0.09	-	1.3
D4a	0.18	-	2.0
D4b	0.29	-	2.0
D5a	0.28	-	2.4
D5b	0.36	-	2.1
D6a	0.38	-	2.3
D6b	0.41	-	2.1
D7a	0.31	-	2.3
D7b	0.38	-	2.4
D8a	0.18	-	2.2
F1a	0.70	-	4.2
F1b	0.40	-	4.5
F1c	0.40	-	4.3
F4a	1.7	0.49	3.5
F4b	1.3	-	3.5
F4c	2.0	-	11.4
F6a	1.8	-	15.2
F6b	2.3	-	15.1

* True lip height values not available for all Toboggan ditches.

APPENDIX C

ANALYSES OF LEAST SQUARES FITS TO EQUATIONS

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Introduction

A complete understanding of this appendix requires some knowledge of standard statistical terminology. In this introduction a short attempt is made to present some of the standard terms for those persons not familiar with them.

A test of significance is a procedure to determine whether a probability level has been exceeded. The probability being considered is the probability that a statistic (anything computed from a sample) differs from a hypothesized value. Variance is a measure of variability of a random variable. It is computed in the same way a moment of inertia is computed, and is, in fact, the moment of inertia of the area between zero and $f(X)$, where $f(X)$ is the density function corresponding to the random variable X .

For example, a test for homogeneity of variances among three depths of burst being significant at the 5-percent level means that if the variances were indeed all equal, the probability is less than 0.05 of getting a statistic as large as, or larger than, the one obtained. If this test among variances yields significance, then usually the statistician assumes the variances are not equal unless additional data show otherwise. Also, to say that the test is not significant does not imply that the data themselves are not significant. It only means that the hypothesis being tested is not contradicted. For example, the test applied below for homogeneity of variances among eight depths of burst is significant for volume per foot of explosive. Hence, the hypothesis of equal variances is contradicted, and the statistician will usually assume that the variances are not equal unless further data or physical considerations refute the assumption.

A regression coefficient as used below is the slope of the straight line obtained by fitting a straight line to the data according to the method of least squares. A test for parallel lines is the same as testing the hypothesis that the slopes of the lines are all equal. If the test for parallelism leads to the conclusion that a set of lines are parallel, then a test for coincidence is made and corresponds to testing that the intersections of the line with the axis $X = 0$ for each of the curves are equal, given that the slopes are already equal.

In the statistical tests used below, deviations from the regression curves are assumed to have a normal probability distribution with a common variance which is independent of X , the independent variable. The tests that are performed, however, are "robust." This means that moderate departures from normality have little effect on the outcome of the tests, and it is necessary to examine the normality assumption more closely only if the statistic is close to the significant probability level. Here the significant probability level chosen is 0.05.

Analysis of Scaled Data

When linear charge weight (in pounds per foot) was plotted on logarithmic paper against volume per foot of explosive (in cubic feet) for various depths, a straight-line relationship (on the log paper) was indicated. For various depths of burst, the lines appeared to be parallel. Similarly, if actual ditch depth or actual ditch width (both in feet) were substituted for volume per foot of explosive, the plots again appeared to be linear and approximately parallel for various depths. Therefore, the logarithms of all the variables were taken, and calculations using least-squares procedures were carried out by using the methods outlined by Quenouille.¹¹

For each of the eight depths of burst, a separate least-squares straight line (on logarithmic paper) was obtained. If these straight lines are then transformed back into the original variables, equations of the form

$$Y = kX^b$$

are obtained. Table C-1 gives the values of k and b for each of these equations.

TABLE C-1

Values of k and b for Separate Regression Lines
(Independent variable X is linear charge weight in pounds per foot)

Dependent variable (Y)	Depth of burst, λ_{DOB}		
	(ft/lbs ^{1/2})	b	k
Volume per foot of explosive (lbs/ft)	0	1.005	0.3104
Volume per foot of explosive (lbs/ft)	0.25	0.9886	0.9703
Volume per foot of explosive (lbs/ft)	0.50	1.018	1.770
Volume per foot of explosive (lbs/ft)	1.00	0.9702	3.534
Volume per foot of explosive (lbs/ft)	1.50	1.093	3.905
Volume per foot of explosive (lbs/ft)	2.00	0.9902	5.644
Volume per foot of explosive (lbs/ft)	2.50	1.070	3.970
Volume per foot of explosive (lbs/ft)	3.00	1.040	2.641
Actual ditch width (ft)	0	0.4792	1.892
Actual ditch width (ft)	0.25	0.5236	2.687
Actual ditch width (ft)	0.50	0.5329	3.678
Actual ditch width (ft)	1.00	0.4643	5.008
Actual ditch width (ft)	1.50	0.5168	5.385
Actual ditch width (ft)	2.00	0.5201	5.818
Actual ditch width (ft)	2.50	0.5673	5.255
Actual ditch width (ft)	3.00	0.4792	5.605
Actual ditch depth (ft)	0	0.5484	0.2927
Actual ditch depth (ft)	0.25	0.4417	0.6254
Actual ditch depth (ft)	0.50	0.4790	0.8277
Actual ditch depth (ft)	1.00	0.4754	1.320
Actual ditch depth (ft)	1.50	0.5107	1.539
Actual ditch depth (ft)	2.00	0.5353	1.212
Actual ditch depth (ft)	2.50	0.6389	0.7787
Actual ditch depth (ft)	3.00	0.8251	0.3782

Individual analyses of variance were prepared for each of the above 24 cases. The analyses of variance for which the unaccounted for estimated mean squares were largest and smallest are recapitulated in Table C-2.

TABLE C-2
Analyses of Variance With Largest and Smallest Unaccounted for
Mean Squares for Regressions Given in Table C-1

Dependent variable	Source of variation	Degrees of freedom	Sum of squares	Estimated mean square
Volume per foot of explosive ($\lambda_{\text{DOB}} = 2.50$)	Ascribable to X	1	5.123454	5.123454
	Unaccounted for	<u>4</u>	<u>0.110283</u>	0.027571
	Total	5	5.233737	
Volume per foot of explosive ($\lambda_{\text{DOB}} = 1.00$)	Ascribable to X	1	5.370154	5.370154
	Unaccounted for	<u>11</u>	<u>0.044550</u>	0.004050
	Total	12	5.414704	
Actual ditch width (ft) ($\lambda_{\text{DOB}} = 0$)	Ascribable to X	1	2.745149	2.745149
	Unaccounted for	<u>16</u>	<u>0.124414</u>	0.007746
	Total	17	2.869563	
Actual ditch width (ft) ($\lambda_{\text{DOB}} = 1.50$)	Ascribable to X	1	1.213274	1.213274
	Unaccounted for	<u>7</u>	<u>0.007472</u>	0.001067
	Total	8	1.220746	
Actual ditch depth (ft) ($\lambda_{\text{DOB}} = 3.0$)	Ascribable to X	1	3.014567	3.014567
	Unaccounted for	<u>4</u>	<u>0.642801</u>	0.160700
	Total	5	3.657368	
Actual ditch depth (ft) ($\lambda_{\text{DOB}} = 1.0$)	Ascribable to X	1	1.289563	1.289563
	Unaccounted for	<u>11</u>	<u>0.016168</u>	0.001470
	Total	12	1.305731	

Although Bartlett's test for homogeneity of variance rejects the hypothesis that variances are the same for the eight depths of burst for each of the three dependent variables, it was thought worthwhile on physical grounds to find that set of regression equations which were parallel for each of the depths of burst. The values of k and b for this calculation are shown in Table C-3.

TABLE C-3

Values of k and b for Parallel Regression Lines
(Independent variable X is linear charge weight in pounds per foot)

Dependent variable	Depth of burst, λ_{DOB}		
	(ft/lbs ^{1/2})	b	k
Volume per foot of explosive (lbs/ft)	0	1.014	0.3063
Volume per foot of explosive (lbs/ft)	0.25	1.014	0.9374
Volume per foot of explosive (lbs/ft)	0.50	1.014	1.779
Volume per foot of explosive (lbs/ft)	1.00	1.014	3.334
Volume per foot of explosive (lbs/ft)	1.50	1.014	4.186
Volume per foot of explosive (lbs/ft)	2.00	1.014	5.493
Volume per foot of explosive (lbs/ft)	2.50	1.014	4.208
Volume per foot of explosive (lbs/ft)	3.00	1.014	2.713
Actual ditch width (ft)	0	0.5096	1.806
Actual ditch width (ft)	0.25	0.5096	2.739
Actual ditch width (ft)	0.50	0.5096	3.784
Actual ditch width (ft)	1.00	0.5096	4.713
Actual ditch width (ft)	1.50	0.5096	5.419
Actual ditch width (ft)	2.00	0.5096	5.889
Actual ditch width (ft)	2.50	0.5096	5.575
Actual ditch width (ft)	3.00	0.5096	5.419
Actual ditch depth (ft)	0	0.5311	0.3005
Actual ditch depth (ft)	0.25	0.5311	0.5531
Actual ditch depth (ft)	0.50	0.5311	0.7766
Actual ditch depth (ft)	1.00	0.5311	1.225
Actual ditch depth (ft)	1.50	0.5311	1.512
Actual ditch depth (ft)	2.00	0.5311	1.218
Actual ditch depth (ft)	2.50	0.5311	0.8696
Actual ditch depth (ft)	3.00	0.5311	0.5243

In order to decide which of the above sets of values of b and k (Tables C-1 or C-3 would be the best to use, complete analyses of variance were computed as shown in Table C-4.

TABLE C-4
Complete Analyses of Variance

Dependent variable	Source of variation	Degrees of freedom	Sum of squares	Estimated mean square
Volume per foot of explosive	Ascribable to regression	1	55.517078	55.517078
	Lack of parallelism	7	0.068201	0.009743
	Lack of coincidence, given parallelism	7	18.532417	2.647488
	Unaccountable	<u>82</u>	<u>1.187528</u>	0.014482
	Total	97	75.305224	
Actual ditch width	Ascribable to regression	1	14.198941	14.198941
	Lack of parallelism	7	0.050655	0.007236
	Lack of coincidence, given parallelism	7	3.174556	0.453508
	Unaccountable	<u>79</u>	<u>0.362084</u>	0.004583
	Total	94	17.786236	
Actual ditch depth	Ascribable to regression	1	15.319815	15.319815
	Lack of parallelism	7	0.581155	0.083022
	Lack of coincidence, given parallelism	7	5.413551	0.773364
	Unaccountable	<u>81</u>	<u>1.196276</u>	0.014769
	Total	96	22.510797	

To test for parallel lines, the ratio of the estimated mean squares for parallelism to the unaccountable is formed. This ratio is then compared with a table of the critical values of the F-distribution at the 5-percent significant level. If the ratio computed exceeds the tabular value, it is concluded that the lines are not parallel. Table C-5 summarizes results of this test.

TABLE C-5
Tests for Parallel Regression Lines

Dependent variable	Ratio	Degrees of freedom	Significant or not
Volume per foot of explosive	0.009743/0.014482	(7, 82)	Not significant
Actual ditch width	0.007236/0.004583 = 1.58	(7, 79)	Not significant
Actual ditch depth	0.083022/0.014769 = 5.62	(7, 81)	Significant at the 5-percent level

Similarly, tests for coincident lines (given parallel lines) were run, and results summarized in Table C-6.

TABLE C-6
Tests for Coincident Regression Lines
(Given parallel lines)

Dependent variable	Ratio	Degrees of freedom	Significant or not
Volume per foot of explosive	2.647488/0.014482 = 182.8	(7, 82)	Significant at the 5-percent level
Actual ditch width	0.453508/0.004583 = 98.9	(7, 79)	Significant at the 5-percent level
Actual ditch depth	0.773364/0.014769 = 52.4	(7, 81)	Significant at the 5-percent level

Since the test for parallel lines (Table C-5) yielded a significant value for actual ditch depth, the analysis for parallel lines was done over for ditch depth with $\lambda_{\text{DOB}} = 2.5$ and $\lambda_{\text{DOB}} = 3.0$ excluded. Tables C-7, C-8, C-9, C-10, and C-11 give results of these analyses.

TABLE C-7
Complete Analysis of Variance
($\lambda_{\text{DOB}} = 2.5$ and $\lambda_{\text{DOB}} = 3.0$ data excluded)

Dependent variable	Source of variation	Degrees of freedom	Sum of squares	Estimated mean square
Actual ditch depth	Ascribable to regression	1	11.069838	11.069838
	Lack of parallelism	5	0.083010	0.016602
	Lack of coincidence, given parallelism	5	5.173032	1.034606
	Unaccountable	74	0.496326	0.006707
	Total	85	16.822206	

TABLE C-8
Test for Parallel Regression Lines
($\lambda_{\text{DOB}} = 2.5$ and $\lambda_{\text{DOB}} = 3.0$ data excluded)

Dependent variable	Ratio	Degrees of freedom	Significant or not
Actual ditch depth	0.016602/0.006707 = 2.48	(5, 74)	Significant at the 5-percent level

TABLE C-9

Test for Coincident Regression Lines
 $(\lambda_{\text{DOB}} = 2.5 \text{ and } \lambda_{\text{DOB}} = 3.0 \text{ data excluded})$

<u>Dependent variable</u>	<u>Ratio</u>	<u>Degrees of freedom</u>	<u>Significant or not</u>
Actual ditch depth	1.034606/0.006707 = 154.3	(5, 74)	Significant at the 5-percent level

TABLE C-10

Values of k and b for Parallel Regression Lines
 $(\lambda_{\text{DOB}} = 2.5 \text{ and } \lambda_{\text{DOB}} = 3.0 \text{ data excluded})$

<u>Dependent variable</u>	<u>Depth of burst, λ_{DOB} (ft/lbs^{1/2})</u>	<u>b</u>	<u>k</u>
Actual ditch depth	0	0.4955	0.3172
Actual ditch depth	0.25	0.4955	0.5808
Actual ditch depth	0.50	0.4955	0.8111
Actual ditch depth	1.00	0.4955	1.285
Actual ditch depth	1.50	0.4955	1.560
Actual ditch depth	2.00	0.4955	1.269

TABLE C-11

Values of k and b for Coincident Regression Lines
 $(\lambda_{\text{DOB}} = 2.5 \text{ and } \lambda_{\text{DOB}} = 3.0 \text{ data excluded})$

<u>Dependent variable*</u>	<u>Depth of burst, λ_{DOB} (ft/lbs^{1/2})</u>	<u>b</u>	<u>k</u>
Actual ditch depth (ft)	0 to 2.0	0.4672	0.7697

* Independent variable X is linear charge weight in pounds per foot

In summary, data for all three dependent variables failed the homogeneity of variance test. For this reason, the best possible fits to the data are given by Table C-1. There is some evidence, however, that for volume and ditch width, parallel regression lines are appropriate. In case there is a theoretical reason for believing this aside from the data, it would be reasonable to use Table C-3 for these two variables. In spite of running the data through again, with $\lambda_{\text{DOB}} = 2.5$ and $\lambda_{\text{DOB}} = 3.0$ eliminated, it appears that ditch depth should not be represented by parallel lines and that Table C-1 should be used for depths. In no case should coincident lines be used, since tests for coincidence were highly significant; i.e., the intersections with $X = 0$ for the various lines were definitely not equal.

In Table C-3 for volume and width and in Table C-10 for depth, a request was made to fit the values of k to an equation of the form

$$k = c\lambda_{\text{DOB}}^2 + d\lambda_{\text{DOB}} + a$$

A regression procedure giving higher weights for $\lambda = 0, 0.25$ was followed and yielded the values shown in Table C-12. Since this was not a fit to experimental data, but to the derived values of k, no analyses of variance were prepared.

TABLE C-12

Values of b and c, d, a for Obtaining k

Dependent variable	b	c	d	a
Volume per foot of explosive (lbs/ft)	1.014	-1.0808	4.3234	0.0929
Actual ditch width (ft)	0.5096	-0.8311	3.6155	1.9302
Actual ditch depth (ft)	0.4955	-0.5072	1.5530	0.2510

Analysis of Permanent Ground Displacement Data

Permanent ground displacement data, where n = 2, 3, 4, 5, 6, 7, and 8, were also analyzed. The result of fitting a straight line to the logarithms of the variables is an equation of the form $y = kX^b$. Table C-13 summarizes these b's and k's.

TABLE C-13

Values of k and b for Separate Regression Lines
(for C-explosive data)

<u>n</u>	<u>b</u>	<u>k</u>
2	-3.462	1.077
3	-5.764	44.27
4	-3.792	2.772
5	-4.170	11.54
6	-4.280	14.11
7	-3.498	6.224
8	-4.563	59.69

An analysis of variance was performed as shown in Table C-14 to determine whether parallel lines could be used for these data.

TABLE C-14

Analysis of Variance of C-Explosive Data for Parallel Regression Lines

<u>Source</u>	<u>Degrees of freedom</u>	<u>Sum of squares</u>	<u>Estimated mean square</u>
Overall regression	1	18.955822	
Lack of parallelism	6	0.614117	0.102353
Unaccountable	<u>41</u>	<u>0.582318</u>	0.014203
Total	48	20.152257	

For Table C-14, the ratio $0.102353/0.014203 = 7.206435$ is significant, and hence parallel lines should not be used for these data. The values of k and b were, however, computed for the parallel lines and are summarized in Table C-15.

TABLE C-15
Values of k and b for Parallel Regression Lines
(for C-explosive data)

<u>n</u>	<u>b</u>	<u>k</u>
2	-4.222	4.788
3	-4.222	2.141
4	-4.222	6.438
5	-4.222	12.82
6	-4.222	12.58
7	-4.222	25.80
8	-4.222	30.55

Analysis of Polynomial Fits to Unscaled Data

If a quadratic or higher degree polynomial is fitted to data, there is more than one regression coefficient. In fact, there is one regression coefficient for each power of the independent variable in the fitted equation. For example, if a general cubic polynomial is fitted to a set of data, the equation takes the form

$$Y = a + b_1X + b_2X^2 + b_3X^3,$$

and b_1 , b_2 , and b_3 are regression coefficients. The constant a gives the intersection of the curve with the axis $X = 0$. In its most general form the definition of regression coefficient also includes a . It is possible to determine which degree polynomial fits the data adequately, yet such that the degree is not unnecessarily large. Generally, given $(n + 1)$ points, a polynomial of degree n or less can be found which will go through all $(n + 1)$ points and the fit is perfect. However, it is usually necessary to find an equation of degree considerably less than n which will do an adequate job. The procedure is to start by fitting a polynomial of the smallest degree (perhaps first degree) which could possibly fit the data adequately. Then the next one or more higher degree polynomials are fitted. An analysis of variance is then prepared. For example, the analysis of variance for ditch depth versus depth of burst is given in Table C-16.

TABLE C-16
Analysis of Variance for Ditch Depth Versus Depth of Burst

<u>Source of variation</u>	<u>Degrees of freedom</u>	<u>Sum of squares</u>	<u>Estimated variance</u>
Ascribable to quadratic effect	2	14.77647	7.38824
Extra ascribable to cubic effect	1	0.02998	0.02998
Extra ascribable to quartic effect	1	0.37624	0.37624
Extra ascribable to quintic effect	1	0.03110	0.03110
Unaccountable	91	2.89485	0.03181
Total	96	18.10864	

Comparison of the ratios of the estimated variance for each of the polynomials to the unaccountable estimated variance with the F-distribution gives significance for the quadratic and quartic cases, but the cubic and quintic cases are not significant. It is not unusual to have a situation, similar to that above, where a cubic essentially is not an improvement over the quadratic, but the quartic is a better fit than the quadratic or cubic. This is due to the different shapes that odd-degree curves have as opposed to those of even degree. If this is the case, it is best to keep fitting higher degree polynomials until two in a row are not significant and then use the polynomial of highest degree which accounted for a significant amount of the sum of squares. For data from which Table C-16 was computed, it was felt that a sixth degree or higher fit should not be used and it was therefore not tested. To have terminated the above analysis strictly on the basis of the data, at least the sixth degree polynomial should have been tried. For data in Table C-16, then, a quartic polynomial was considered adequate. The quintic was not used, since it did not significantly fit the data better than did the quartic.

The procedure as outlined above was followed for each of the dependent variables considered, and the appropriate degree polynomial (less than sixth degree) was chosen, as shown in Table C-17.

TABLE C-17
Degree of Polynomial Chosen for Fits to
Various Dependent Variables

<u>Dependent variable</u>	<u>Degree of polynomial</u>
Crater volume	4
Crater diameter	2
Crater depth	3
Ditch volume	3
Ditch width	2
Ditch depth	4

APPENDIX D

MILITARY LINE CHARGE DATA

In 1946 a report was issued on a project sponsored by the National Defense Research Committee which investigated various phenomena related to standard military line charges.³ Of interest from a Toboggan standpoint is the ditching portion of that project. All line charges were detonated on the surface of a sandy-clay loam which varied in moisture content. Actual charges in their standard casings were used. (Whether end or multidetonations were employed is not known.)

The data show a great spread when plotted for scaling purposes as the Toboggan data were plotted. This is quite possibly due to variations in explosive type and casing. Table D-1 gives the raw test data. Figure D-1 shows scaling plots for ditch width and depth. A straight line fit made in accordance with the methods described in Appendix C yields a width function of

$$a = 2.44 W^{0.50}$$

and a depth function of

$$D = 0.67 W^{0.35}$$

Military ditches created by detonating the charge on the ground surface were always wider and deeper than similar ditches created in Yucca Lake bed during Project Toboggan.

TABLE D-1

Military Line Charge Ditch Data

Charge	Linear charge wt (lbs/ft)	Length of charge (ft)	Round No.	Average width (ft)	Average depth (ft)
Detonating cord	0.078	30.0	2	0.4 - 1.0	0.25
PETN			6	0.8	0.3
Infantry Snake	0.64	100.0	1	3.0	0.9
(Magnesium alloy case)			2	1.4	----
98.5/1.5 TNT/NG			3	1.0	----
			5	2.0	----
Infantry hose	0.47	49.8	2	2.0	0.4
EL-389-B			4	3.3	0.7
			5	3.0	0.7
			7	3.0	0.4

TABLE D-1 (cont)

Charge	Linear charge wt (lbs/ft)	Length of charge (ft)	Round No.	Average width (ft)	Average depth (ft)
Tank hose	4.5	153.5	1	3.1	1.4
EL-389-B			2	5.0	----
			3	6.0	1.4
			4	5.5	1.5
			5	5.5	----
			6	6.0	1.45
Bangalore	1.8	100.0	1	2.2	0.7
Torpedoes			2	2.6	0.6
Amatol 80/20			3	2.6	0.7
			4	2.5	0.6
			5	2.2	0.5
All charges surface-burst					
M-3 Snake	14.4	320.0	1	8.2	2.03
(aluminum case)		230.0	2	8.3	1.85
Amatol 80/20		160.0	3	8.2	1.74
		160.0	4	8.6	1.82
M-3 Snake	14.4	20.0	1	13.5	3.0
(aluminum case)			2	9.0	1.4
Amatol 80/20			3	9.5	1.5
			4	10.0	1.8
M2A1 Snake	14.4	20.0	1	10.7	2.4
(steel case)			2	----	1.6
Amatol 80/20			3	10.0	1.8
			4	10.4	1.4
M2A1 bare	14.4	20.0	1	9.0	2.0
Amatol 80/20			2	9.0	1.4
			3	9.5	1.5
			4	9.0	1.4
M2 Snake	14.4	20.0	1	7.0	1.9
Bangalore loaded			2	9.0	1.5
(steel case)			3	9.5	1.6
Amatol 80/20			4	10.0	----
M2 Snake	10.0	20.0	1	8.0	1.4
(steel case)			2	8.5	1.4
Amatol 80/20			3	8.5	1.4

Figure D-1. Ditch Width and Depth Versus Charge Weight for Surface-Burst Military Line Charges

APPENDIX E

SHATTER WEDGES

A number of the Toboggan ditches contained wedge-shaped slickensided fragments. Representative samples (Table E-1) were selected from C and B ditches and examined in detail at Sandia Laboratory. Table E-1 gives the significant data for each of these specimens. Typical specimens are shown in Figure E-1.

TABLE E-1
Shatter Wedge Data

<u>Specimen number</u>	<u>Weight (grams)</u>	<u>Volume (cc)</u>	<u>Density (grams/cc)</u>	<u>Range of wedge angle (degrees)</u>
B2-I	4.03	2.05	1.97	9-21
B2-II	4.37	2.39	1.83	20-22
B2-III	5.38	2.71	1.99	19
B2-IV	4.78	2.56	1.87	21-30
B2-V	4.02	2.11	1.91	12-15
C2-I	7.43	3.72	2.00	14-18
C2-II	3.34	1.61	2.08	10-14
C2-III	4.29	2.14	2.01	10-16
C2-IV	5.12	2.39	2.14	11-18
C2-V	8.26	4.32	1.91	10-11
C2-VI	4.47	2.67	1.67	8-9
C2-VII	8.36	4.06	2.06	6-16
C2-VIII	4.63	2.30	2.01	14-17

Similar fragments have been studied extensively by Dr. Robert Dietz of the Navy Electronics Laboratory.^{12, 13} The cone-shaped rock fragments observed by Dietz appear to result when a high-velocity shock wave moves through the parent rock. The resulting fragment, called a "shatter cone," is a striated cup-and-cone structure. These curious structures have been identified by Dietz as occurring naturally in various sedimentary rocks and in rock surrounding both chemical and nuclear explosions.

The peculiar fragments, or "shatter wedges," found in the Yucca Lake ditches probably result from a shocking phenomenon similar to that which causes shatter cones. The wedge shape is attributable to a cylindrical divergent shock wave, whereas the cone-shaped structures would result from a spherical divergent shock front. Cones have been observed by Dietz for explosives having detonation velocities ranging from 5000 to 8000 m/sec.¹³ Detonation velocity for Toboggan explosives was approximately 7000 meters per second.

Shatter wedges were observed in A, B, and C ditches at the Toboggan site. The size of the fragments appeared to vary directly with the size of the linear charge which caused them. As noted in Table E-1 there was variation in the wedge angle for each C and B specimen. The total wedge angle range was 6 to 18 degrees for the C specimens and 9 to 30 degrees for the B wedges. Dietz found the apical angle of shatter cones to range from 75 to 90 degrees. The shatter wedges exhibit significantly smaller angles than do shatter cones.

Toboggan fragments were easily broken when handled, the soil material usually breaking along interior slickensided surfaces and cracks found normal to these surfaces. The additional interior slickensided surfaces were not always parallel to the exterior surface of the original shatter wedge.

Density determinations run on the shatter wedge specimens range from 115 to 134 pounds per cubic foot. Field density tests taken at various depths in a test trench on Yucca Lake gave densities ranging from 64 to 90 pounds per cubic foot. The greatest maximum density (113 pounds per cubic foot) was determined for material taken from a depth of 20 feet. Obviously, tremendous compressive forces must have existed during the ditch formation period to yield fragments having densities as high as those determined for the shatter wedges.

Dietz¹² points out that shatter cones have a preferred orientation; i. e., they point opposite to the direction of shock-wave propagation. In other words, they point toward the origin of the shock wave. Observations at the Toboggan site indicated that shatter wedges also point toward the explosive. Detonation products found on many of the shatter wedges indicate that they were formed adjacent to the original line charge.

To explain the shatter wedge mechanisms, it is necessary to quote Dietz on his explanation for shatter cones:¹²

"By applying Hartman's law, which states in part that under rotational forces the acute angle formed by shear planes in brittle material is bisected by the axis of maximum stress, it is apparent that the axis of a shear cone was also the axis of maximum stress. Thus such cones are produced by compression parallel to the axis. This type of failure is well known to mechanical engineers, who test the crushing strength of cement cylinders. Conical fracturing permits a rock stratum to become thinner at the expense of elongation. To accomplish this thinning by lowering the top of a stratum with respect to the bottom of the same stratum it is geometrically necessary that the cone axes point upward."

This same explanation can probably be applied to the formation of shatter wedges. The question as to whether or not the Yucca medium can be considered a brittle material as mentioned in Hartman's law still remains, however. In any case, the compressive forces originating from linear charges are probably applied along the surface of parallel cylindrical planes. It would be interesting to determine whether shatter wedges could be created by detonation of linear charges in rock. Perhaps a laboratory experiment could be devised in which the explosive was inserted into a cylinder of brittle material (if possible, a true rock). Such an experiment would eliminate backfill inconsistencies encountered for linear charges in rock.

Figure E-1. Typical Shatter Wedge Specimens for C and B Ditches

APPENDIX F
ENGINEERING, CONSTRUCTION, AND OPERATIONAL PHASES

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Site Location and Preparation

The Toboggan program was conducted on the dry lake bed of Yucca Flat at the Nevada Test Site. A testing area was selected near the northeast corner of the lake and centered about coordinates N807,300 and E692,662. The area measured roughly one-half mile square. The lake bed was selected because of the uniformity of the material both laterally and vertically. It consists of fine silt and clay with some lenses of coarse and fine gravel which have been deposited over many years. The surface is flat, and elevations over the entire lake bed vary less than 0.5 feet. Within this area the ditches were surveyed and staked out. All ditches were oriented in a north-south direction to provide uniformity of operation. Such an orientation also provided ideal lighting conditions for photographic work. One other feature that influenced the orientation was a project of microbarograph coverage. Pressures from the ends of the ditches in addition to pressures propagated perpendicular to the ditch longitudinal axis could be monitored without the necessity of moving the microbarograph stations.

It was decided that the most practical and economical method of excavation was to dig all ditches less than three feet deep by hand labor; for those deeper a mechanical ditch digger was used. This machine could dig a trench 20 inches wide, up to ten feet deep. Since the deepest shots were at the 20-foot depth, it was necessary to use a back hoe on those ditches at depths between 10 and 20 feet. This machine dug a ditch 4 feet wide. Both of these pieces of equipment are shown in Figure F-1. There were forty-two ditches dug for Phase I and fifty-six for Phase II. Also, twenty-five 8-pound HE spheres were fired at depths down to 5 feet. For these a conventional, hand post-hole digger was used, while a gas-fired earth auger was used on the deeper holes.

(a) mechanical ditch digger

(b) back hoe

Figure F-1. Ditch-Digging Equipment

On all of the deeper ditches the machine excavated to within approximately one foot of the final depth. The ditch bottom was brought to finished grade by hand labor. This method provided accurate control of the depth of charge placement.

It is noteworthy that of the 123 individual firings made there were no misfires, and that all equipment performed satisfactorily.

Explosives, of which six different charge weights were used, were stored in the underground igloo in Frenchman's Flat, approximately 15 miles from the test area. Jet perforators and electric blasting caps were kept in temporary storage in a portable igloo kept at Yucca Lake. During handling operations, the HE was removed from the igloo and unboxed. It was then built into bundles of the required cross-sectional area, taped together, and stored in a wood-lined iron vault which had been modified for this purpose. Qualified HE handlers were supplied by Reynolds Electrical and Engineering Company for this operation. The storage vault was carefully swept and cleaned each day, and all scrap HE was collected and taken to the burn area together with the empty boxes. At the burn area, which was within a mile of the vault, all debris was stacked in a pile and burned periodically. A special HE truck with a wood-lined bed was used to transport the HE from the storage area to the detonation site. All safety regulations governing vehicles of this type were observed.

Loading Procedures

Loading procedures varied according to the depths of the ditches being fired. On those ditches less than 10 feet deep the HE was transported from the igloo and unloaded on the ground beside the ditch. At this point the loading crew, which normally consisted of four men, placed the HE along the bottom of the ditch. Two men on the surface handed the HE bundles down to the men in the ditch. Care was taken to insure that the charges were in end-to-end contact with each other to insure high-order detonation. The "B" and "C" types of explosive were shipped wrapped in thin wax paper which was left on the explosive during loading and firing. A crane was used on ditches deeper than 10 feet. A box to hold 700 pounds of explosive was designed so that the ends could be removed after it was lowered by the crane into the ditch. The explosive was loaded into the box directly from the HE truck (Figure F-2).

On Phase I shots the jet perforator was securely taped to the block at the north end of the linear charge. On Phase II, eight jet perforators were equally spaced and taped on the linear charge regardless of ditch length.

Individual pieces of 49-grain Primacord, all of equal length, were attached to the jet perforators and extended to the surface. On ditches deeper than 10 feet the Primacord was fed through 1-inch thinwall tubing to protect it during backfill tamping. A 1-foot layer of fine sand was next placed over the explosive, providing a cushion for tamping. On the deep ditches this cushion of sand was 2 feet thick.

Figure F-2. Crane Used in Lowering Explosive into Ditch

Backfill Preparation and Placement

The backfill material used was the same material that had been removed when the ditch was dug and was piled alongside the ditch. Before it could be used it was necessary to replace the moisture that had been lost through evaporation. To accomplish this, a motor grader was used to move the material away from the loaded ditch and spread it evenly, approximately 2 feet thick. After a tank truck had watered the spread-out material liberally, a motorized pulverizer equipped with a reel of rotating blades which breaks up all large clumps, mixed the material evenly as it moved along the pile. This three-step operation was repeated until the original moisture content of the soil was reached. This was determined by tests performed by Holmes and Narver field engineers (Figure F-3). On a number of shallow ditches that did not entail handling a large amount of material, this could be accomplished by manually adding water to the soil and mixing it with shovels to the desired consistency. The material was then placed in the ditch and tamped.

On the large ditches the next step was for the blade to work the pile over to the ditch and then blade it into the ditch in lifts 10 to 12 inches thick (Figure F-4). Three different types of tampers were used on the backfill. On the narrow ditches a hand tamper equipped with a steel foot, 6 inches square and 1 inch thick, was used. On the wider and deeper ditches, air tampers were used. Air was supplied by a compressor positioned close to the ditch.

Figure F-3. Motorized Pulverizer

Up to eight tampers could be supplied by one compressor (Figure F-5). A third type which was tried and discarded was a self-contained gas engine-powered tamper with a tamping foot 24 x 24 inches. The objection was that the vibration induced by this tamper caused the side walls of the ditch to slough off, producing a safety hazard for personnel working in the ditch (Figure F-5c).

Figure F-4. Backfill Being Bladed into Ditch

The requirement for placement of the backfill material specified that 90 percent of original in-place density be secured. By using the tamping method outlined above, this was achieved on all ditches and, in most cases, densities were closer to 95 percent. A number of backfill density and moisture content determinations were made as the backfilling operation proceeded. Results are given in Table B-5 of Appendix B. A test made in the original lake bed material showed an undisturbed dry density of 75.7 lbs/ft³ with a moisture content of 10 percent.

When the ditch was completely filled and tamped, all excess dirt was removed from the area. The site was then barricaded and left for a minimum of 24 hours before firing. It was felt that this would allow the backfill moisture to penetrate the ditch walls to some extent and create a bonding effect.

(a) air tampers in use on backfill placement

(c) gas engine-powered tamper

(b) air tamping operation

Figure F-5. Tamping Operations

Safety Aspects

A number of safety features were incorporated as part of the standard operating procedure. As loading was completed on each ditch, it was protected by wooden barricades for its full length. "Explosive" and "Danger" signs were placed on the barricades and removed just prior to firing. All personnel in the area were evacuated to the safe distance as specified in the arming and firing plan.

During the construction period, the side walls on some ditches sloughed to some extent. This necessitated shoring up the walls with 4- x 8-foot plywood sheets and screw jack spreaders before any personnel were allowed in the ditch. These panels were removed individually as the backfilling proceeded, thus insuring protection of the workmen at all times (Figure F-6).

Figure F-6. Shoring of Ditch Walls

Because of explosives in the area and firing cables laid on the surface, it became necessary to rigidly control traffic flow. To accomplish this, a berm was constructed around the perimeter of the operational area with access permitted at two points only.

Soils Investigation

In order to describe accurately the medium in which the linear ditching experiment was conducted, it was necessary to perform field and laboratory tests. Twining Laboratories, Inc. was selected by Holmes and Narver, Inc. to perform the investigation. A location was picked for the test trench within the operational area and the trench was dug under the direction of a Twining Laboratories representative. The significant portion of the Twining report is included as Appendix A.

Photography

Sandia Laboratory photographers provided all coverage on this program. Pictures showing progress of construction were taken; also, all phases of HE handling, loading of ditches, and types of equipment and material in use were photographed.

After each ditch was fired, documentary still pictures were taken of the resulting crater, from both side and overhead positions. For this purpose, a truck-mounted hydra-lift was used. This had a telescoping boom and could place the photographer about 30 feet in the air over the ditch. However, since a majority of the ditches could not be covered in one "set-up," it was necessary to position the hydra-lift at a number of locations along the ditch and secure overlapping pictures. From this a mosaic was made up that included the complete ditch. A 4- x 5-inch graphic camera was used for this coverage. The survey party laid out string lines which established the longitudinal axis of the ditch and the ends of the explosive. A survey rod and a title board which listed information as to shot number, data, charge depth, length, and total explosive weight were placed in the field of view of the camera. Care was taken to ensure that all pictures were made before vehicle or foot traffic was allowed in the vicinity of the newly formed crater.

Motion picture coverage was provided on three ditches in the "C" series to observe early ground motion and any observable phenomena resulting from the multidetonation system of firing. A photographic backboard was erected 50 feet behind these ditches and extended the full ditch length to provide contrast. It was constructed of 4- x 8-foot plywood panels painted black and nailed to a framework of 4- x 4-inch posts which were sunk in the ground. Cameras used were a 35 mm Fastax at 5000 fps, a 16 mm Fastax at 6000 fps, a Photosonic at 500 fps, and a Warrick at 1400 fps. All documentary film was processed and printed in the field by Sandia's mobile photographic laboratory. Motion picture film was shipped to Sandia Laboratory for processing.

Four ditches in the "C" series, 100, 125, 150, and 175 feet in length, respectively, were too long to be photographed adequately from the hydra-lift. A helicopter was rented from Las Vegas Airways to carry a Sandia photographer aloft to secure overhead pictures (Figure F-7).

Figure F-7. Helicopter Used for Overhead Photography

Survey

A preshot survey was made of the area around each ditch in order to establish original surface elevations. Also, control points were staked to be used for the postshot survey. As soon as possible after each shot, the survey party moved into the area and stretched string lines for the photographers. After all pictures were taken, the survey control points were relocated and a postshot survey was made of the crater area. On the larger ditches hundreds of elevations were taken to insure adequate reflection of surface changes.

Permanent displacement measurements were made on selected ditches. To secure these, 8-inch spikes were driven into the ground with the heads flush with the surface. This was done on the longitudinal axis of the ditch and on a line oriented 90 degrees to the longitudinal axis at a point midway along the length of the ditch. Both preshot and postshot elevations were taken on these spikes. Spacing between spikes was 1 foot on normal ditches and 2 feet on the larger ones.

Topographic maps of each ditch were prepared from the survey data. Experiment criteria called for six equal contours within the ditch and two contours of the crater lip having an accuracy of ± 10 percent of the contour interval. In addition, 11- x 17-inch film-positive reductions of finished sepias were furnished Sandia Laboratory.

All engineering and survey work was performed by Holmes and Harver, Incorporated. Construction support was provided by Reynolds Electrical and Engineering Company, which also supplied qualified technicians to operate the microbarograph stations and high-explosive handlers to assist Sandia Laboratory personnel.

APPENDIX G

ARMING AND FIRING

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Firing Systems

Three systems were utilized for firing the charges, although two of these were essentially the same. The systems consisted of a commercial condenser discharge blasting machine and a special eight-point firing system designed and fabricated by Sandia.

The condenser discharge unit used was a duPont Model CD-32-1. A set of internally contained batteries is used to charge the storage capacitors to 320 volts. This particular model is rated to fire up to 30 blasting caps in parallel on circuits not exceeding three ohms resistance (Figure G-1). The unit is designed with two switches, one to allow charging of the capacitors and the other to initiate firing. The principal safety feature is that the "ready" switch must be held down before the circuit is complete for discharging the capacitors when the "fire" switch is depressed. One cable was used to the junction box where leads to each cap were connected. This machine was utilized on tests when no ground-motion photography was required and proved very satisfactory.

Figure G-1. Condenser Discharge Unit Firing System

A special eight-point system was designed and fabricated at Sandia to fire the linear charges. Figure G-2 is a schematic diagram of the system which employs a high-voltage power supply to charge the capacitors to 2500 volts. The high voltage is developed to obtain good initiation-time simultaneity between the eight blasting caps. When the arm switch is closed, 115 v AC is applied to the power supply, and the capacitors are charged. The charge voltage is monitored on the calibrated meter to determine readiness for firing.

When full charge is reached, the fire switch actuates the relay and dumps the capacitor into the eight lines to the caps. The A/S monitor lamp indicates the correct position of the fire relay before charging of the storage capacitors. The camera control was not used in this application, but the fire signal was applied directly to the fire relay. For good simultaneity, cable lengths to the blasting caps are kept to a minimum. To accomplish this, the firing system is divided into a combined control and monitor unit; the other unit consists of the power supply, energy storage capacitors, fire switch, and load connectors. The control unit is placed at the safe-separation distance from the shot, and a multiconductor cable connects it to the other unit placed close to the blast.

Figure G-2. High-Voltage Firing System

The other system used was essentially the same as that described above except for the application of the fire signal. For tests in which high-speed cameras were used to photograph the test, the camera operation had to be synchronized with the firing so that the cameras would be operating at the correct speed. A satisfactory method was worked out for using the fire signal to actuate the camera control by closing a latching relay to start the cameras. At the end of the preset delay time, another relay closed and applied power to actuate the fire relay. The delay setting was determined by dry runs and the timer adjusted so that the cameras were operating at the desired speed when the blasting caps were initiated. This method was successfully employed on all of the shots requiring high-speed photography to record ground-motion phenomena.

Arming

Arming of charges in preparation for firing consisted of several operations. The first involved placing the initiator on the high-explosive charges before backfilling could be performed. After the backfill operation, the firing system was tested for operation and the blasting caps connected to the primacord and into the firing system.

After the high explosive had been placed in position and checked for alignment and physical contact between sections, jet perforators were installed. The charge length was divided so that the same amount of HE would be detonated by each of the eight perforators. The initiator was placed with the jet vertical into the charge. It was taped to the charge in such a manner that backfill would not move it or fill the cone with dirt. A loop of 49-grain primacord was run through the eye to the surface of the lake bed. In the very deep ditches, the primacord was fed to the surface through thinwall conduit to protect it during backfill and tamping operations.

The firing system was tested for operation each time before arming. A dry run or test was accomplished by firing at least one blasting cap with normal operation. Under these conditions the control cable was completely checked after being rolled out onto the lake bed. Each system was tested initially several times for firing of all eight caps. The simultaneity of firing was proved by taking high-speed motion pictures of the blasting caps bursting. Both systems would furnish firing of all points in less than one millisecond. Each blasting cap was tested for continuity with a standard blasting galvanometer. After the firing system was "safed" and checked for voltage on the output connections, the caps were connected to the circuit by "crimp-on" splices. In each case the cap was taped between the ends of the two pieces of the primacord loop from each perforator. The charge was then armed and was ready for firing.

Firing

Firing was accomplished locally after the area surrounding the blast site had been cleared, arming completed, time coordinated with other agencies, and a radio countdown supplied.

The danger area was defined as 144 times the cube root of the charge weight in pounds. Using this formula, personnel would experience less than one-quarter psi overpressure, even when the charge was detonated on the surface. Since the HE was not encased and the lake bed is composed of silt, a missile hazard did not exist. Inasmuch as the test area is flat and there are no structures, it was easy to determine if personnel were within the danger area. Individuals concerned with the test maintained blocks at main access roads into the test area of the dry lake and were in radio contact with the control to report clearance and readiness to fire.

Proposed shot time was established and coordinated with other users in the area usually on the day before firing, particularly for the large shots. This alerted other agencies to bypass the area during the test and allowed them to reschedule activities. When roadblocks were set and the area cleared, a countdown to firing was furnished over the Sandia radio net. This was a manual countdown, usually during the last minute only. When the shot was being monitored by microbarograph, the countdown was utilized for starting recorders at the correct time. After the shot was detonated, roadblocks were maintained until the immediate area around the blast was checked for unburned high explosives. The arming party re-entered the area and monitored the crater, after which access for normal operations and preparations for other tests was resumed.

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