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Emplacement and Firing of High-explosive Charges and Crater Measurements

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PROJECT PRE-BUGGY

PNE 302

EMPLACEMENT AND FIRING OF HIGH-EXPLOSIVE CHARGES AND CRATER
MEASUREMENTS

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ABSTRACT

17 Six 1,000-pound high-explosive (HE) charges, each containing a capsule of radioactive tracer (Lanthanum 140), were detonated at depths varying from 15.0 to 21.4 feet in desert alluvium to permit selection of the optimum depth of burst commensurate with crater size and shape and radioactivity release. Using the burst depth thus selected, four row shots, consisting of five 1,000-pound HE charges in each row, were fired with intercharge spacing varying from 1.0 to 1.5 apparent crater radii to determine the optimum spacing to produce a channel of satisfactory size and proportion and relatively free of irregularities. 2 The immediate purpose of the experiment was to aid in the design of a proposed nuclear row-charge event (Project Buggy).

2/ Selection, fabrication, emplacement, and firing of the charges are discussed, along with the technique used to measure the apparent and true craters and zones of subsurface disturbance. 16 references/end

The selected depth of burst was 19.8 feet, or a scaled depth of approximately $180 \text{ ft/kt}^{1/3.4}$. The optimum charge spacing was determined to be about one and one-eighth

apparent crater radii. Comparison is made with results of previous row-charge experiments, and graphs of channel parameters are developed. Channel depth was found to be very sensitive to charge spacing, but channel width varied only slightly with spacing. It is concluded that a usable channel with suitable dimensions can be excavated by means of nuclear explosives.

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PREFACE

Participation of the U. S. Army Engineer Waterways Experiment Station (WES) in Project Pre-Buggy was under the sponsorship of the U. S. Army Engineer Nuclear Cratering Group, Lt. Col. Ernest Graves, Jr., Director. The experiment was conducted at the U. S. Atomic Energy Commission's Nevada Test Site (NTS), to which WES sent a field party to perform emplacement and firing of the high-explosive (HE) charges and to make crater measurements. Photography and radioactive-tracer experimentation were accomplished by the University of California Lawrence Radiation Laboratory (Nevada) and are reported upon, along with other facets of the experiment, in Reference 1.

The fieldwork for this project began in November 1962 in Area 10, NTS, but was delayed when the first two shots showed heterogeneity and some cementation of subsurface strata, which caused considerably shallower craters than those predicted. After a change of location to Area 5, testing was resumed in December 1962, and the last shot was fired in February 1963.

Project Officer for the WES portion of the experiment was Mr. A. D. Rooke, Jr. Mr. S. E. Bartlett was responsible for emplacement and firing of the charges, and Messrs. J. A. Conway and L. K. Davis performed the crater investigations. They were assisted by Messrs. W. M. Gay, W. H. Sadler, Jr., G. H. Williams, A. G. Reno, and G. J. Stevens, and by Pfc. W. F. Ballard and Pvt. M. A. Vispi. Messrs. A. L. Mathews and T. B. Goode supervised drilling of the necessary boreholes for the sand-column array. Conduct of the fieldwork and preparation of this report were under the direct supervision of Mr. J. N. Strange, Scientific Advisor for the Pre-Buggy test series, Mr. G. L. Arbuthnot, Jr., and Mr. F. R. Brown.

Col. Alex G. Sutton, Jr., was Director of the WES during the investigation and the preparation of this report. Mr. J. B. Tiffany was Technical Director.

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DEFINITIONS, ABBREVIATIONS, AND NOTATION

Definitions

Apparent crater	The visible crater formed by an explosion.
Crater depth	Depth of the crater at surface ground zero (SGZ) as measured from the original ground surface.
Crater radius	The average radius of a crater as measured horizontally from SGZ to the crater's intersection with original ground surface.
Depth of burst	Depth below original ground elevation at SGZ to the charge center of gravity.
Ejecta (throwout)	Material ejected from the crater by the force of the explosion.
Elastic zone	The zone in which no permanent deformation of the medium occurs.

Fallback

The material between the true and apparent crater boundaries.

Surface ground zero

That point on the ground surface directly above the center of the buried charge (the epicenter of the charge).

Lip

The distinctly raised portion of the earth immediately surrounding an apparent crater.

It is formed by ejecta and plastic flow of the medium (upthrust), and it usually becomes discontinuous about two crater radii outward from SGZ.

Plastic zone

The zone in which the medium surrounding a crater is permanently displaced (has flowed plastically) but is without visible rupture.

Rupture zone

The zone of material surrounding a crater characterized by extreme fracturing.

Scalloping (cusping)	The formation of ridges between charge locations on the sides and bottom of an explosion-formed channel.
True crater	The explosion crater profile prior to fallback of a portion of the dissociated medium.

Abbreviations

AEC	U. S. Atomic Energy Commission
CDU	Capacitor discharge unit
C-4	Composition 4 (explosive)
Dob	Depth of burst
HE	High explosive
kt	Kiloton(s)
NE	Nuclear explosive
NM	Nitromethane
NTS	AEC Nevada Test Site
SGZ	Surface ground zero
TNT	Trinitrotoluene

Notation

D_a	Apparent crater depth
D_c	Apparent channel depth at

	charge location
D_i	Apparent channel depth midway between charge locations
D_t	True crater depth
H_{al}	Height of crater lip
H_{tl}	Height of upthrust medium surrounding the crater
L_a	Apparent length of an explosively formed channel
R_a	Apparent crater radius
R_t	Radius of true crater
R_{zt}	Radius of the true crater cavity directly below the charge position
S	Spacing between row charges (center to center)
V_a	Apparent volume of crater or channel
W	Charge weight in pounds of TNT, or equivalent charge weight of another explosive expressed in terms of TNT

W_{al}	Width of crater lip
W_c	Apparent channel width at charge location
W_i	Apparent channel width midway between charge locations
Z	Charge depth of burst

Additionally, the prime notation (') indicates a scaled relation, and a value shown beneath a bar ($\bar{}$) is intended to denote an average (arithmetic mean).

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

The objective of the Pre-Buggy chemical explosives experiment was to extend current cratering knowledge by obtaining data on crater dimensions and the venting of explosion products from several experiments involving spherical charges which were uniformly spaced in a row and detonated in alluvium. Emphasis was placed on learning the effect of varying the spacing of charges for a depth of burst (Dob) slightly greater than optimum. The immediate purpose of the experiment was to apply the information thus obtained in the design of a proposed nuclear row-charge event (Project Buggy).

1.2 BACKGROUND AND THEORY

Although no completely satisfactory theoretical explanation of the cratering phenomenon has as yet been published, much is known and predictable concerning the mechanics of crater formation (References 2 through 6). It has been established, both theoretically and experimentally, that small cratering explosions do not accurately model larger

detonations, or vice versa, especially where different energy sources, i.e. high explosive (HE) and nuclear explosive (NE), are involved. A fundamental reason for this is the conflict of requirements in Froude's and Mach's scaling laws (Reference 7). Another important reason is the manner in which the explosive energy is partitioned to the surrounding media. When these differences are accounted for, certain useful relations can be established concerning crater dimensions which are found to hold reasonably well throughout a rather broad range of explosive yields. In the absence of an expressive theory, most correlative efforts make use of empirically determined scaling laws, based upon some fractional exponent of trinitrotoluene (TNT) charge weight or yield (W). Scaling by $W^{1/3.4}$ is used in most parts of this report, as such scaling is currently considered most applicable to the range of yields involved.

In order to design Project Buggy, it was necessary to refine the knowledge which had been gained in earlier, smaller scale ditching experiments (References 8 and 9). Project Pre-Buggy was conceived and executed for this purpose, using 1,000-lb chemical (HE) charges, each containing a radioactive "source" of Lanthanum 140, to

model nuclear charges. In order to have a soil medium (desert alluvium) closely resembling that in which Project Buggy is planned, Area 5 of the U. S. Atomic Energy Commission's Nevada Test Site (NTS), shown in Figure 1.1 was selected as a site for the tests. This is a flat expanse of desert alluvium, mixed with some fines, cobbles, and small boulders (see Appendix A).

Previous experience in nuclear events had indicated that the percentage of radioactivity released to the atmosphere from underground shots varied from about 10 percent for a Dob to apparent crater depth ratio (D_{ob}/D_a) of 2 to about 0.1 percent for a ratio of 4 (Reference 1). Accordingly, six Pre-Buggy single-charge Dob's were selected in the range shown in Figure 1.2. Note the relative positions of the shots on the curves in Figure 1.2 with respect to optimum, as well as the values of D_{ob}/D_a . For the row charges, an appropriate Dob was selected from the results of the single-charge experiments, thus fixing the other row-charge parameters. Spacings of 1.00, 1.25, and 1.50 crater radii were planned for the ditching experiment. A fourth spacing of 1.125 crater radii was added later.

Although apparent crater depth and diameter were the primary considerations in the design of Pre-Buggy, it was also desired that more complete information be obtained on the craters thus formed, both from the standpoint of expanding general knowledge on this subject as well as insuring the formation of stable, useful craters and side slopes. In this respect it should be noted that a crater exhibits several zones of dissociation and deformation of the surrounding earth (References 2, 3, and 10). These are the apparent and true craters and the rupture and plastic zones illustrated in Figure 1.3. To study these phenomena, use was made of a technique originally developed by the U. S. Army's Ballistics Research Laboratory (Reference 11). Vertical columns of colored sand were imbedded in the earth in the vicinity of the surface ground zero (SGZ). Postshot excavation and examination of these columns revealed the extent of the permanent deformation within the medium.

The search for a suitable high explosive led to Nitromethane (CH_3NO_2) (referred to herein as NM), a commercial solvent. Most available cratering curves for shots detonated at NTS are based upon events using TNT or nuclear energy, and NM exhibits explosive characteristics strikingly

similar to those of TNT, thus permitting reference to existing curves. On an energy basis NM may be considered as 1.1 times as powerful as TNT (i.e. releases 1.1 times as much energy per pound as TNT). This value was derived from two Livermore Radiation Laboratory (LRL) documents: The Pinot A report (COL 6 PL 5525) dated 22 April 1960 and a memorandum by Mr. L. B. Ballou (COL 6 PL 5481) dated 9 March 1960. The NM/TNT energy ratio may vary from 1.08 to 1.37 depending on the density of the TNT. The 1.1 ratio represents an average figure. Like TNT, NM is insensitive to shock under natural conditions of temperature and pressure, and is therefore safe to transport and store. Although it reacts with some materials, this was not found to be a serious disadvantage. NM will burn, but burning alone does not produce detonation. It has the additional advantage that, as a liquid, it instantly assumes the shape of its container. Appendix B lists the more important physical and explosive properties of NM. In order to represent a point source of energy as closely as possible, the charge shape chosen was that of a sphere, and the means of initiation were centrally located within the spherical container to insure uniform radial propagation of the detonation wave and subsequent shock.

Figure 1.1 Pre-Buggy location map.

Figure 1.2 Apparent crater dimensions versus depth of burst for NTS alluvium, showing the selected range of Pre-Bugby shot depths. Data taken from a least squares fit of HE data in Reference 2.

Figure 1.3 Idealized cross section of typical explosion-formed crater.

CHAPTER 2

PROCEDURE

2.1 PREPARATION AND EMPLACEMENT OF HE CHARGES

2.1.1 Charge Components and Assembly. Each charge container consisted of an aluminum alloy sphere 3 feet in diameter. A booster assembly, shaped as a right circular cylinder, was inserted into the sphere through an access hole. The basic NM charge was boosted by 3.5 pounds of Composition 4 (C-4). Initiation of each charge was provided by two Atomic Energy Commission (AEC) detonators (SE-1), to which tetryl pellets were affixed to insure detonation of the booster. A system of pipes placed in the main-charge cover plate and in the booster cover (Figure 2.1) permitted filling of the main-charge container and access for the detonator wires, the primacord line (used as a backup firing system), and the radioactive-source capsule. Assembly of the charges, except for the addition of the NM, was accomplished in Sugar Bunker, a structure in Area 5 especially designed for the preparation of explosive charges. The NM was added after the charge container had been seated at proper depth in its borehole. A step-by-step safety plan

governed not only the procedure of charge assembly, but emplacement and firing as well. Figures 2.2 through 2.8 illustrate the principal steps in charge assembly.

2.1.2 Emplacement of Charges. The prepared charge container and the NM were transported to the firing site from separate locations and in separate vehicles, the former from Sugar Bunker and the latter from NTS Storage Yard No. 3. The firing site was laid out by Holmes and Narver, Inc., on-site contractors, and the charge boreholes were drilled with a Reynolds Electrical and Engineering Co. auger bucket. Each borehole was drilled about 2 feet deeper than the design Dob, which was taken to be the depth below original ground elevation to the charge center of gravity, thus providing about 6 inches of extra depth to insure proper positioning of the charge. The charge container was transported and lowered with the aid of a modified 2-1/2-ton truck. All access lines were brought to the surface. A fine silica sand was then poured around the charge container as it was suspended in position, insuring proper seating. Depth of the charge was measured with a tape measure attached to the radioactive-source insertion tube. Readings were taken from the top of the corrugated metal pipe used as borehole casing,

or by reading the tape with a level. When the charge container was well seated, the NM was added directly from 55-gallon drums by gravity flow. After the filling operation, stemming of the charge was accomplished by backfilling of the borehole with a coarse, unwashed sand obtained at NTS, which was tamped to provide a backfill density of about 103 pcf, compared to a density of about 110 pcf for the native medium. During stemming, the primacord line was coiled at various levels in the borehole to insure that its faster detonation did not cause premature venting of the main explosion. Figure 2.9 shows the charge seated in its borehole, while Figures 2.10 through 2.14 illustrate the emplacement process.

2.1.3 Firing Procedure. A schematic layout of the electrical firing system, designed to initiate the detonators with a high degree of simultaneity, is shown in Figure 2.15. The detonators and zero-time marker (flashbulb or ball of C-4) were all fired by means of a capacitor discharge unit (CDU) which was in turn activated remotely by a trigger unit at the firing point. Both the trigger unit and CDU, which were interdependent, had keys which provided positive lockout of the system. A 15-kw gasoline-powered

generator supplied 110-volt, 60-cycle alternating current to the trigger unit and thence to the CDU by means of an eight-conductor steel-core cable. The triggering pulse which activated the CDU was carried by a smaller cable, RG-58/U. After the final prearming electrical continuity checks (Figure 2.16), the charge was "seeded" with its radioactive source and the insertion tube was backfilled with fine silica sand. Upon order of the Technical Director of the Pre-Buggy project or his representative, arming, countdown, and firing were accomplished, all strictly governed by the AEC-approved safety procedure. Figures 2.17 through 2.19 show the CDU near surface ground zero (SGZ) and the arrangement of the firing point. An auxiliary firing system, consisting of primacord leading into the booster, was available to be fired by detonator from the surface should the primary system fail; however, no such failures occurred. Figures 2.20 and 2.21 show typical explosions.

2.2 CRATER MEASUREMENTS

2.2.1 Emplacement of Sand-Column Arrays. Colored sand-column arrays were emplaced for a deep, shallow, and median-depth shot for the single charges and on two

row shots according to the typical plans shown in Figure 2.22. These arrays were considered the minimum consistent with the determination of true crater formations and subsurface disturbance. Four-inch-diameter boreholes for the columns were drilled by personnel of the U. S. Army Engineer Waterways Experiment Station (WES). Where necessary, casing of the holes was employed to keep them open; however, the casing was withdrawn as the holes were filled. The backfill consisted of an unwashed sand obtained at NTS, to which a mixture of lime, water, and vegetable dye was added. The backfill was designed to closely approximate the density and strength of the native soil medium. Where instability of the boreholes made it necessary, backfilling and tamping were done with the drill rig over the hole, using the drill stem as the tamp and pulling up the casing just ahead of backfilling operations. Where casing of holes was not required, backfilling operations were performed separately. Thin layers of asphalt cold mix were added at intervals during backfilling of the columns and their depths were measured, thus enabling postshot determination of vertical, as well as lateral, disturbance. Typical drilling and backfilling operations

are shown in Figures 2.23 and 2.24.

2.2.2 Survey Measurements of Apparent Craters. Pre-shot and postshot survey profiles for each event were performed by Holmes and Narver, Inc., or by the WES field party. This permitted rapid determination of apparent crater dimensions and provided a check on the crater map made by aerial stereophotography.

2.2.3 Aerial Stereophotography. Contour maps of all shot areas were provided by American Aerial Surveys, Inc., by means of aerial stereophotography.

2.2.4 Excavation of Sand Columns. Excavation of the sand columns was begun immediately after completion of the single-shot test series. All single-charge column arrays and the longitudinal array of columns on the row charges were excavated by means of a trench dug by a bulldozer and a self-propelled scraper (Figures 2.25 through 2.27). A track-mounted backhoe was utilized to excavate the column radii perpendicular to the row-charge axes. The trenches were cut at an offset distance of approximately 2 feet from the line of columns, the remaining excavation of the sand columns being done by hand.

The final exposure and measurement of the columns were

considerably hampered by the sloughing of the loose fallback material above the true crater. It was impractical to remove this material prior to the trench excavation due to the possibility of damage to the columns. Therefore, the trenches were cut in lifts of 2 to 5 feet to minimize this difficulty. Also, due to the low moisture content of the soil, columns within the rupture zone had a tendency to collapse soon after exposure.

The trenches were cut as deep as safety permitted. Further excavation would have necessitated the removal of an excessive amount of material from the sides of the trenches and therefore was discontinued.

Conventional survey equipment was employed to determine the final positions of the columns. Preshot reference points were reestablished near the craters to provide horizontal and vertical control.

Figure 2.1 Schematic diagram of booster assembly for 1,000-pound, spherical NM charge.

Figure 2.2 Packing the booster container with C-4. The booster cover assembly (Figure 2.1) is on the left. Note the seated "O"-ring on the booster container which provided a seal against the surrounding NM which would otherwise dissolve the C-4.

Figure 2.3 Introduction of the primacord, which served as an auxiliary firing system, into the booster container.

Figure 2.4 Emplacement of one of the two AEC detonators used in each booster. A tetryl pellet is glued to its base. Note tools used to fashion wells in the C-4.

Figure 2.5 Mating booster container to the booster cover assembly. The pipe extending into the center of the booster provides a receptacle for the radioactive-tracer capsule.

Figure 2.6 Introduction of booster assembly into the main-charge container. The spherical container consisted of two spun aluminum-alloy hemispheres, 1/8 inch thick, joined and banded by heliarc welds. Lines extending above the booster assembly are detonator wires (left) and primacord (right).

Figure 2.7 Addition of Adiprene and Moca, a sealing compound and catalyst, respectively, to primacord and detonator-wire access pipes. This step insured that primacord and detonator lines would not be accidentally pulled from the booster.

Figure 2.8 Completed charge assembly. Sleeving has been added to detonator wires and primacord line for their protection during backfilling of the borehole. Also, fill and vent lines have been affixed to their respective pipes on the booster cover assembly. Two opposing eyes on charge-container cover plate are used for suspension of the container during emplacement.

Figure 2.9 Schematic diagram of charge emplacement.

Figure 2.10 Preparing to lower the charge container into firing position.

Figure 2.11 Charge container being lowered downhole into firing position. Tracer-insertion tube was added in sections as charge was lowered.

Figure 2.12 NM being transferred from drum to emplaced charge container. Container is still suspended from crane to prevent displacement during filling operation.

Figure 2.13 Stemming the charge hole. Backfill material was tamped to approximate in situ soil density.

Figure 2.14 Emplaced-charge site, showing access pipe (with funnel) for radioactive source, lockout box for detonator leads, and bag of silica sand for stemming the access pipe.

Figure 2.15 Schematic plan view of initiation system.

Figure 2.16 Continuity test of firing cable.

Figure 2.17 Emplacement of CDU. Note protective box, padding, and sandbags. Both trigger and eight-conductor electrical lines can be seen in background.

Figure 2.18 Firing control complex. From left to right are the Rad-Safe trailer, firing trailers, and weather monitoring trailer. The power generator is at far right.

Figure 2.19 Firing point in control complex.

Figure 2.20 Single-charge detonation.

Figure 2.21 Row-charge detonation. View is normal to the line of charges.

Figure 2.23 WES drill rig boring holes for sand-column array.

Figure 2.24 Backfilling and hand-tamping the colored sand in boreholes. Note graduated tamp used for this work. The colored sand mixture was approximately 54 percent sand, 25 percent slaked lime, 20 percent water, and 1 percent vegetable dye by weight.

Figure 2.25 Bulldozer pushing scraper in excavation of row A.

Figure 2.26 Excavated trench through single-charge No. 4 crater. Note sloughed material within true crater area. Right wall of trench is east-west center line of crater.

Figure 2.27 Excavated trench through row A. Note sloughing of fallback material within true crater. Left wall of trench is east-west center line of crater.

CHAPTER 3

RESULTS

3.1 EFFECTIVENESS OF NM CHARGES

No unusual problems were encountered in the use of NM. All detonations were apparently high order and complete. The characteristics of NM are given in Appendix B. Based on its characteristics, NM was considered to be 1.1 times as powerful as TNT, and charge weights were adjusted accordingly where comparative data plots were made. As explained on page 18, the value of 1.1 was considered an average value and depended upon the density of the TNT.

3.2 APPARENT CRATER MEASUREMENTS

3.2.1 Single Charges. Table 3.1 shows all single-charge apparent crater data, as recorded by postshot surveys, along with pertinent information concerning each shot. Figure 3.1 shows the apparent crater profiles for all Pre-Buggy single charges. The apparent crater dimensions for all single shots compared very favorably with the predicted dimensions, except for shot No. 5. High-speed photography of the shot No. 5 detonation indicated that a partial stemming failure occurred, resulting in a much shallower apparent crater than predicted.

In general, the single-charge craters were symmetrical with smooth, uniform interior slopes of very loose, fine-grained material which was very unstable in the deeper craters. In contrast to the fairly uniform interior slopes, the lip deposits were quite irregular, with large "rays" extending outward radially (see Figure 3.2). Figures 3.3 through 3.14 are preshot and postshot contour maps of the Area 5 single-charge crater areas.

3.2.2 Row Shots. The apparent crater results for the four row shots are tabulated in Table 3.2. The channel measurements given were calculated by averaging the widths and depths at each charge position and midway between charges.

Figures 3.15 and 3.16 are comparative profiles of the row-charge craters. Profiles were taken along three axes: (1) through the longitudinal axis of the charges, (2) normal to the longitudinal axis through the center charge, and (3) normal to the longitudinal axis midway between the second and third (center) charges.

Row A was the only row crater (channel) which resembled the single-charge crater of the same Dob in its interior slope. The other three channels were shallow enough for the fallback material to become stable as it fell in place. In

row A, however, much of the late-falling material sloughed to the center of the crater, resulting in a V-shaped crater with smooth but steep and unstable slopes. There was also a sharp transition between the interior slope and the lip, and between the slope and the bottom of the crater. The B, C, and D row craters were much shallower than the row A crater, with no distinct transitions between the interior slopes and the bottoms of the craters, and only slight transitions at the lips.

An unusual characteristic of all the row craters was a lack of fallback material on the ground surface at each end of the craters (see Figure 3.17).

In the majority of the row shots, a sliding failure of the upper portion of the fallback slope was observed at each end of the crater. The slope failure created a shelf about 2 feet in depth and several inches below the original ground level.

Figures 3.18 through 3.25 are contour maps of the row-charge crater areas. Figure 3.26 is an aerial oblique of a portion of the test area, and Figures 3.27 through 3.29 are aerial stereopairs of the row-shot craters. Figure 3.30 shows the firing area of the Pre-Buggy test

site, with all craters and channels.

3.2.3 Comparison of TNT and NM Charges. After the completion of the Pre-Buggy NM shots, two TNT charges were detonated in the same area (Figure 1.1) to compare the craters resulting from detonations of the two types of chemical explosives. The TNT charges were cast spheres weighing approximately 960 pounds each, and were detonated at the optimum Dob (19.8 feet) selected for the NM charges. While TNT and NM have similar characteristics, especially when a slight correction factor is applied to compensate for the energy release, the craters resulting from the TNT charges were remarkably dissimilar to the NM craters. As can be seen in Figure 3.1, both TNT craters were extremely shallow and irregular and significantly shallower than the NM craters. This difference was quite unexpected and can only be attributed to improper stemming and/or possibly incomplete detonation of the TNT. Further tests with TNT were not made but should check the crater results with NM as evidenced by other tests. The close similarity of TNT and NM results shown in Figures 4.1 and 4.2 justifies the use of NM.

3.3 TRUE CRATERS AND ZONES OF DEFORMATION

3.3.1 Accuracy of Measurements. Definitions and

descriptions of the true crater, rupture zone, and plastic zone as applied to this report can be found in the list of definitions, abbreviations, and notation preceding the text of this report and in Figure 1.3. In most cases, apparent crater dimensions and true crater depths are accurate to the nearest 0.2 foot; true crater radii were more difficult to ascertain and, where shown, are considered accurate to the nearest 2 feet. Due to the limited depth of postshot excavation, the envelope of plastic response could, in most cases, be only approximated. The rupture zone was found to be very difficult to identify in desert alluvium, and therefore has not been included in the sand-column plots. Where identified (near the charge position), however, its thickness appeared to be approximately 1 to 2 feet.

3.3.2 Sand-Column Recovery. Figures 3.31 through 3.39 are postshot plots of the sand columns. In both the single- and row-charge craters, the columns 35 and 50 feet from SGZ showed little or no displacement. The lower portions of the 50-foot columns did not move at all, and the 35-foot columns generally moved outward as a unit approximately a few tenths of a foot or less. All other columns evidenced gross deformation from the explosions, varying from complete

dissociation to slight displacement in the vertical plane only.

The SGZ columns were compressed into a funnel shape, while the 4- through 24-foot columns reflected the plastic flowage and shear failures resulting from the pressure and shock of the detonation; the severity of deformation generally decreased with radial distance from the charge. An interesting discovery was that of fairly intact sand columns within the fallback.

Sand-column recovery was considered successful with the exception of those columns on the radii perpendicular to the row-charge axes. Since the true craters on these radii were deeper than anticipated, only small portions of the columns were recovered.

The sand columns were extremely useful in providing information for defining the limits of the apparent and true craters while the asphalt layers located therein indicated areas of upthrust or compression. Lateral displacement of the columns in the plastic zone is indicative of areas subjected to shearing or compressive forces although it is difficult to delineate any definite trends because of the non-homogeneity of the soil mass.

3.3.3 True Crater Measurements, Single-Charge Craters.

The true crater profiles for the three measured single-charge craters are presented in Figure 3.40. The cup-shaped depression in the true craters directly below the charge position was evident in varying degrees in all the craters excavated. In all cases, the depression consisted of very hard, compacted soil which contrasted sharply with the loose fallback material within and above it. As the true crater profile progressed upward and outward from the bottom depression, the division between fallback and the true crater became less discernible.

3.3.4 True Crater Measurements, Row-Shot Channels.

Although the depths were similar, there were distinct differences between the radii of the true craters and deformation zones for the single-charge craters and those of the row-shot channels. On the row A channel, the true crater radii at the channel ends were several feet less than the single-charge true crater radius at the same Dob. Conversely, the true crater radii normal to the charge axes in both rows A and C were several feet greater than the single-charge true crater radius.

Profiles of the bottoms of the row-shot true craters

(Figures 3.41 and 3.42), as inferred from the mapping of the sand columns, show a scalloping effect between charge locations where the medium was compressed but not displaced. This should not affect the hydraulic efficiency of the channel to carry flow or the stability of the side slopes. A comparison of the profiles shows that for the wider spacing of row C the mounds between charges are approximately the same height but wider and flatter than those in the row A channel.

True crater data, and computed volumes of fallback material, are summarized in Table 3.3.

TABLE 3.1 APPARENT CRATER DIMENSIONS, SINGLE CHARGES

Event No.:	Test	1	2	3	4	5 ^a	6
Hole No. ^b :	-	5	3	1	4	2	6
NM Charge Weight, pounds	1,017	1,003	1,011	1,011	1,009	1,016	1,015
TNT Equivalent Charge Weight ^c , pounds	1,119	1,103	1,112	1,112	1,110	1,118	1,117
Depth of Burst, feet	15.0	15.0	16.6	18.2	19.8	21.4	19.6
Scaled Depth of Burst, ft/kt ^{1/3.4}	136	136	150	165	179	194	177
Apparent Crater Depth, feet	10.9	9.7	9.1	7.8	9.4	4.1	8.3
Scaled Apparent Crater Depth, ft/kt ^{1/3.4}	99	80	82	71	85	37	75
Apparent Crater Radius, feet	22.7	21.0	21.8	20.9	20.6	19.7	20.7
Scaled Apparent Crater Radius, ft/kt ^{1/3.4}	205	190	197	189	186	178	187
Apparent Crater Volume, yd ³	---	243	280	216	242	98	225
Scaled Apparent Crater Volume, yd ³ /kt ^{0.88}	---	1.8×10^5	2.1×10^5	1.6×10^5	1.8×10^5	7.2×10^4	1.7×10^5

^a Photography indicated a partial stemming failure.^b Included only for correlation with numbering system in Reference 1.^c NM charge weight $\times 1.1$.

TABLE 3.2 APPARENT CHANNEL DIMENSIONS, ROW SHOTS

Event:	Row A	Row B	Row C	Row D
Average NM Charge Weight, pounds	1,016	1,023	1,007	1,004
Average TNT Equivalent Charge Weight ^a , pounds	1,118	1,125	1,108	1,114
Design Depth of Burst ^b , feet	19.8	19.8	19.8	19.8
Scaled Design Depth of Burst, ft/kt ^{1/3.4}	179	179	180	180
Design Charge Spacing in Predicted Crater Radii	1.00	1.50	1.25	1.125
Design Charge Spacing ^b , feet	20.6	30.9	25.8	23.2
Scaled Design Charge Spacing, ft/kt ^{1/3.4}	186	279	234	210
Average Apparent Channel Depth ^c , feet	12.1	4.9	4.4	6.4
Scaled Average Apparent Channel Depth, ft/kt ^{1/3.4}	109	44	40	58
Average Apparent Channel Width ^c , feet	44.5	33.1	38.6	42.8
Scaled Average Apparent Channel Width, ft/kt ^{1/3.4}	402	299	350	388
Apparent Channel Volume, yd ³	1,300	480	660	905
Scaled Apparent Channel Volume, yd ³ /kt ^{0.88}	9.8×10^5	3.5×10^5	4.9×10^5	6.8×10^5

^a Average NM charge weight $\times 1.1$.^b "As-built" dimensions varied < 3.5 percent.^c Obtained by averaging measurements taken at charge positions and midway between charge positions.

TABLE 3.3 TRUE CRATER DATA, ALL EVENTS

Profile was too indistinct to allow reliable measurement of true crater radius between charge positions.

Event:	Single Charge No.			Row Shot	
	1	3	4	A	C
True Crater Depth, feet					
Below Charge	24.1	24.9	25.8	27.0 ^a	26.5 ^a
Midway Between Charges	--	--	--	21.5 ^b	20.2 ^b
Scaled True Crater Depth, ft/kt ^{1/3.4}					
Below Charge	219	226	234	244	240
Midway Between Charges	--	--	--	194	183
True Crater Radius, feet					
Center Normal to Line of Charges	26	28	25	27	31
End Along Line of Charges	--	--	--	23	28
Scaled True Crater Radius, ft/kt ^{1/3.4}					
Center Normal to Line of Charges	236	254	226	244	281
End Along Line of Charges	--	--	--	208	254
True Crater Volume, yd ³	637	748	702	3,530	4,420
Scaled True Crater Volume, yd ³ /kt ^{0.88}	4.7×10^5	5.5×10^5	5.2×10^5	2.6×10^6	3.3×10^6
Volume of Fallback, yd ³	394	532	460	2,230	3,760
Scaled Volume of Fallback, yd ³ /kt ^{0.88}	2.9×10^5	3.9×10^5	3.4×10^5	1.6×10^6	2.8×10^6
Radius of True Crater Cavity, ft	9.1	6.7	6.0	7.2	6.7

^a Average of two measurements beneath center and end charges.

^b ±1 foot. See paragraph 3.3.1 for accuracy of other measurements.

Figure 3.1 Comparative apparent crater cross sections of single charges.

Figure 3.2 Apparent crater of test charge. Note the large "ray" of lip material in the foreground extending toward the camera.

Figure 3.4 Preshot contours (in feet above msl) of single shot No. 2 crater area.

Figure 3.8 Preshot contours (in feet above msl)
of single shot No. 6 crater area.

Figure 3.9 Postshot contours (in feet above msl) of single shot No. 1 crater.

Figure 3.11 Postshot contours (in feet above msl) of single shot No. 3 crater.

Figure 3.13 Postshot contours (in feet above msl) of single shot No. 5 crater.

Figure 3.15 Comparative cross sections of row-charge apparent channels along center line of charges.

Figure 3.16 Comparative cross sections normal to charge axis of row-charge apparent channels.

Figure 3.17 View from west end of row A channel.
Large pieces of soil in foreground indicate a
subsurface layer of hardpan.

Figure 3.18 Preshot contour map of row A ($\bar{R}_a = 1.0$).

Figure 3.19 Preshot contour map of row B ($R_a = 1.5$).

Figure 3.20 Preshot contour map of row C ($R_a = 1.25$).

Figure 3.22 Postshot contours (in feet msl) of row A channel. Dashed line indicates access road.

Figure 3.23 Postshot contours (in feet msl) of row B channel.

Figure 3.25 Postshot contours (in feet msl) of row D channel.

Figure 3.26 Portion of the Pre-Buggy test area.
From bottom: single charge No. 2, row B, excavation trench through single charge No. 4, single charge No. 1, row A, and single charge No. 6.

Figure 3.27 Aerial stereopair of row A channel. For three-dimensional effect, use standard stereoscope. Single-charge craters 6 and 1 appear at top and bottom, respectively. Excavation has already begun on the latter.

Figure 3.28 Aerial stereopair of row B channel. Single charge No. 2 crater appears at left. Excavation is that of single charge No. 4 crater.

Figure 3.29 Aerial stereopair of rows C and D channels. Single-charge craters shown near the center of the photograph are, from top to bottom: No. 2, test shot, and No. 5. Portions of the TNT craters can be seen at the left. Excavation at lower right is soil sampling test pit.

Figure 3.30 Aerial view of Pre-Buggy test site (Area 5), showing completed events.
 "SC" refers to "single charge."

Figure 3.31 Postshot sand-column positions for single shot No. 1.

Figure 3.32 Postshot sand-column positions for single shot No. 3.

Figure 3.33 Postshot sand-column positions for single shot No. 4.

Figure 3.34 Postshot sand-column positions for row A longitudinal radial.

Figure 3.35 Postshot sand-column positions for row A north radial.

Figure 3.36 Postshot sand-column positions for row A south radial.

Figure 3.37 Postshot sand-column positions for row C longitudinal radial.

Figure 3.38 Postshot sand-column positions for row C north radial.

Figure 3.39 Postshot sand-column positions for row C south radial.

Figure 3.40 Center-line cross sections of single-charge craters, showing zones of deformation.

Figure 3.41 Longitudinal center-line cross sections of row shots A and C.

Figure 3.42 Transverse cross sections of row shots A and C.

CHAPTER 4

DISCUSSION

4.1 CHARGE EMPLACEMENT AND FIRING

Although no particular difficulties were encountered in the actual emplacement and firing of the Pre-Buggy events, the cratering results in a few instances were apparently influenced by inconsistencies in the charge stemming. The stemming failure of single charge No. 5 was attributed to insufficient tamping of the borehole backfill material, which allowed the explosion gases to vent prematurely through the emplacement hole. In addition, high-speed photography of the row-charge explosions indicated that the five charges did not vent simultaneously; this failure may be attributed only to stemming inconsistencies, local inhomogeneities of the medium, or a combination of these factors. In row B, there was a time lag of ~ 0.1 second between the venting of the first and last charges, the longest lag experienced. As mentioned previously, failure of the TNT charges to agree with the NM data also seems to be due to improper stemming and/or incomplete detonation of the TNT sphere. Results of other test series with TNT appear to check NM results.

4.2 COMPARISON WITH PREVIOUS SINGLE-CHARGE DATA

If the Pre-Buggy crater relations are to be considered representative of the general mechanics of crater formation, regardless of charge yield, it is necessary to transfer the Pre-Buggy data to basic cratering-capability plots. Dimensional analysis suggests that cratering dimensions are proportional to the cube root of the yield (W), and experience indicates that $W^{1/3.4}$ is probably as accurate a scaling denominator as any for yields in the range of 1 kt. In Figures 4.1 and 4.2, the Pre-Buggy data have been superimposed on a plot of cratering data obtained in previous tests in NTS alluvium (Reference 12). The curves in the figures have been drawn so as to favor the larger shots. For Pre-Buggy single charges, the apparent depth curve appears slightly high; however, Pre-Buggy apparent radii fall very close to the scaled curve.

Since the Pre-Buggy row shots were detonated at a constant Dob, the values of their apparent crater depths and radii were superimposed on the single-charge curves in Figures 4.1 and 4.2 in order to ascertain the vertical spread of data resulting from the variation in charge spacing. On the scaled depth curve, the row-shot data

spread extends well above and below the single-charge spread. On the scaled radius curve, however, there is little difference between the spread of single-charge and row-shot data, with the exception of row B data, which fall somewhat below the curve.

4.3 TRUE CRATERS AND ZONES OF DEFORMATION

The sand columns revealed the boundary of actual dissociation of the medium which delineates the true crater, all material above this boundary having been separated and lifted from its original position by the expanding explosion gases or by spalling (near the surface). This separation was not always as violent as had been previously supposed, however, as was evidenced by the discovery of fairly intact sand columns several feet in length within the fallback.

The results of direct compression were best shown by the SGZ sand columns, which were forced downward into funnel-like shapes, and those columns immediately adjacent to the charge, which were generally "bowed" about the charge location. A secondary effect of the compressive pressures generated by the explosion is the upward and outward "flowing" of the soil medium, particularly in the region

immediately below the true crater. It is within this region that patterns of behavior of the columns are somewhat difficult to determine.. This may be attributed to the generally unconsolidated nature of the soil, as well as to local inhomogeneities. Shears were in evidence in varying degrees throughout most of the deformation zone except directly below the charge. In the outer columns where plastic flowage appeared negligible, horizontal shears were predominant, apparently occurring along planes of weakness in sand layers or caliche..

While the asphalt layers in the sand columns revealed significant vertical movement, excavation was not deep enough to establish the lower limits of this movement.. From the measurements that were made, however, it seems certain that movement in the soil near and below the charge position tends more to the vertical direction and less to the horizontal with increasing depth..

4.4 EFFECTS OF CHARGE SPACING ON CRATER DIMENSIONS

Single charge No. 4 (Dob 19.8 feet) was selected as the optimum among the single-charge series for the purposes of this experiment.. Using the dimensions of single charge No. 4

as a comparator, Figure 4.3 graphically illustrates the cratering-capability ratios of the row shots within the range of interest for Pre-Buggy. Since yield and Dob were constant for these events, differences in the ratios can be attributed to spacing of the charges. A standard of channel measurement has been adopted wherein dimensions of width and depth are averaged on the basis of readings taken at and midway between the charge locations (paragraph 3.2.2). The length ratio reflects the contribution to channel length of each charge in the row (total apparent channel length expressed in terms of single shot No. 4 apparent diameter/number of charges), and the volume curve similarly shows the contribution of each individual charge as compared to the volume of the single-shot crater at Dob = 19.8 feet.

4.5 SCALLOPING OF ROW-SHOT CHANNELS

The tendency of an explosively excavated channel to scallop (cusp) on the bottom and sides between charges usually detracts from the practical value of the channel, especially if it is to contain flowing water. The smoother the walls of the channel the greater the carrying capacity in the passage of flow; conversely, the rougher the walls of

the channel, the less the capacity. Also as the channel becomes rougher, eddies are set up along the sides and bottom which confine the main thread of the current to the center of the channel; this is desirable as far as erosive action of the current on the sides and bottom of the channel is concerned but unsatisfactory for navigation conditions. For cuts through mountainous areas for highways or railways the side wall roughness becomes of less importance. The irregularities, although not great, are apparent in Figures 3.26 through 3.29. The degree of scalloping with respect to channel depth and width was calculated by means of the following formulas:

$$\text{Percent scalloping (depth)} = \frac{\bar{D}_c - \bar{D}_i}{\bar{D}_c} \times 100 \quad (4.1)$$

$$\text{Percent scalloping (width)} = \frac{\bar{W}_c - \bar{W}_i}{\bar{W}_c} \times 100 \quad (4.2)$$

where $\bar{D}_c$ and $\bar{W}_c$ are the average apparent crater depth and width at the charge locations and $\bar{D}_i$ and $\bar{W}_i$ are similar measurements midway between charge locations. For these formulas, the end charges were not considered. Scalloping of the craters ranged from maximums of 25 percent and 8 percent for depth and width, respectively, for the row B (charge spacing 1.5) channel to minimums of 2 percent for depth in the row D

channel and -2 percent for width in the row A (charge spacing 1.125) channel, where the intercharge channel width was slightly greater than that found at the charge locations.

Figure 4.1 Comparison of Pre-Buggy apparent crater depths with those of other shots in NTS alluvium (Reference 12). Single charge No. 5, which had a stemming failure, is omitted.

Figure 4.2 Comparison of Pre-Buggy apparent crater radii with those of other shots in NTS alluvium (Reference 12). Single charge No. 5, which had a stemming failure, is omitted.

Figure 4.3 Effects of charge spacing on crater dimensions for $D_{ob} = 19.8$ feet.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The Pre-Buggy HE experiment added to the available knowledge concerning the mechanics and effects of ditching (row) charges. The conclusions of prime importance to the design of Project Buggy are as follows:

1. At a Dob slightly below single-charge optimum, a charge spacing of about one and one-eighth single-charge apparent crater radii will provide a fairly smooth channel with apparent width to depth ratio of approximately 6.7.

2. At a spacing of one crater radius, the apparent channel width increases only gradually, but the apparent depth increases sharply.

3. An increase in spacing beyond one and one-eighth crater radii will cause a decrease in apparent depth and average apparent width.

Earth-moving efficiency per charge in a row shot with the Pre-Buggy Dob and with a charge spacing of $1.0 R_a$ is greater (by 7 percent) than that for a comparable single charge, but this efficiency decreases rapidly up to a

spacing of $1.5 R_a$ (60 percent less).

Charge spacings and Dob's necessary to produce desired channel dimensions can be approximated from data obtained in Pre-Buggy and other row-shot experiments. These data, limited to playa and desert alluvium but including a more recent ditching experiment (Reference 16), indicate that the optimum Dob necessary to produce any desired apparent channel depth is deeper than that for a comparable single-charge crater, while the optimum Dob's are about the same in effecting desired apparent width.

Looking toward future larger ditching experiments, the use of nuclear charges appears feasible as a means of creating a usable ship channel, subject to investigation of the associated problems of radioactivity release, slope stability, etc.

5.2 RECOMMENDATIONS

It is recommended that future row-charge cratering experiments be studied closely to (1) verify and/or refine the data and conclusions from Pre-Buggy and (2) determine more precisely the zones of permanent earth deformation beyond the true crater.

APPENDIX A
SITE GEOLOGY

The Pre-Buggy test site in Area 5, NTS, was located on a talus slope of a typical desert alluvial, bahada-type deposit. Field classification of soil in this area indicated primarily a sand or silt with considerable amounts of gravel and occasional cobbles or boulders. A few boulders found in the Pre-Buggy craters and excavations ranged up to 18 inches in diameter. Visual inspection of the excavation trenches revealed considerable stratification, with layers ranging from a few inches to 2 feet in depth. Density tests in the area indicated dry densities ranging from 80 to 120 pcf. Water content of the density samples ranged from 4 to 7 percent.

APPENDIX B

PROPERTIES OF NITROMETHANE (NM)

The more important physical properties of NM, as specified in its purchase for Pre-Buggy, are shown in Table B.1. The utility of NM as an explosive has only recently been demonstrated (Reference 13). While the addition of certain chemicals may sensitize or desensitize NM, it is, under natural (as opposed to laboratory) conditions of temperature and pressure, insensitive to shock. The only known possibility of accidental detonation lies in impact of a high-velocity object against a thick-walled NM container. The drums in which it is shipped and stored are designed to preclude the possibility of sufficient pressure buildup to cause an explosion.

NM is flammable, and burns with a slow, luminous flame. It is corrosive to some metals and will react with some materials (rubber and certain plastics). It is also mildly toxic to the skin, and inhalation of concentrations greater than 100 parts per million should be avoided.

Specific energy (by weight) of NM is approximately 114 percent that of TNT. Its velocity of detonation is slightly

less than that of TNT, about 6,200 m/sec compared with 6,400 m/sec (Reference 14). For correlative purposes in this experiment, the NM energy release per pound was considered as 1.1 times that of TNT.

TABLE B.1 PHYSICAL PROPERTIES OF NITROMETHANE (CH_3NO_2) (Reference 15)

Purity ^a , pct by weight, minimum	95
Nitroparaffin ^a , pct by weight, minimum	99
Specific gravity, 25/25 ^b degrees C	1.124 to 1.129
Specific gravity at 20/20 degrees C	1.39
Acidity as acetic acid, pct by weight, maximum	0.1
Water, pct by weight, maximum	0.1
Color, APHA ^c , maximum	20
Distillation range, degrees C, at 760 mm of mercury, 90 pct minimum	100 to 103
Molecular weight	61.04
Boiling point (at 760 mm of mercury), degrees C	101.2
Azeotrope with water, boiling point, degrees C	83.6
Nitroparaffin in azeotrope, pct by weight	77.1
Vapor pressure at 20 degrees C, mm	27.8
Evaporation rate, by volume ^d	139
Freezing point, degrees C	-29
Density of vapors (air = 1.00)	2.11
Weight per U. S. gallon at 68 degrees F, pounds	9.48
Coefficient of expansion, per degree F	0.00064
Refractive index, n_D ^e , at 20 degrees C	1.3818
Surface tension at 20 degrees C, dynes/cm	37.0
Viscosity at 25 degrees C, centipoises	0.631
Heat of combustion, kcal/mole	169.4
Heat of vaporization at 30 degrees C, cal/gm	143.3
Heat capacity at 25 degrees C, cal/gm	0.422
Dielectric constant at 30 degrees C	35.87
Ignition temperature, degrees F	785
Flash point, degrees F (tag open cup)	112
pH 0.01 mole aqueous solution at 25 degrees C	6.4
Solubility in water at 20 degrees C, pct by volume	9.5
Solubility of water in nitroparaffin at 20 degrees C, pct by volume	2.2
Lower flammability limits, pct by volume in air at 92.5 degrees F	7.3

^a Determined by mass spectrometer.^b Referred to H_2O , both liquids at 25 degrees C.^c American Public Health Association.^d n-butyl acetate = 100.^e Referred to yellow "D" line of sodium.

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