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Physical Characteristics of Craters From  
Near-Surface Nuclear Detonations

Headquarters Field Command  
Defense Atomic Support Agency  
Sandia Base, Albuquerque, New Mexico

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## FOREWORD

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## *FOREWORD*

This report presents the final results of one of the projects participating in the military-effect programs of Operation Hardtack. Overall information about this and the other military-effect projects can be obtained from WT-1660, the "Summary Report of the Commander, Task Unit 3." This technical summary includes: (1) tables listing each detonation with its yield, type, environment, meteorological conditions, etc.; (2) maps showing shot locations; (3) discussions of results by programs; (4) summaries of objectives, procedures, results, etc., for all projects; and (5) a listing of project reports for the military-effect programs.

## ***ABSTRACT***

The objective of this project was to measure and correlate with existing data the physical characteristics of craters (radius, depth, lip height and width, throwout, and permanent vertical ground-surface displacement surrounding the crater) resulting from near-surface nuclear detonations.

Primary participation was on Shots Koa, Cactus, and Fig, the only land-surface bursts of Operation Hardtack. Dimensions of the craters were determined by topographic, lead-line, and aerial-stereographic surveys. Secondary participation included fathometer surveys of barge shots Linden, Oak, Yellowwood, Butternut, and Holly.

When the crater dimensions of the above shots were compared to adjusted dimensions taken from the crater curves of TM 23-200 it was found that Shot Cactus and Shot Fig crater data compared favorably, but the Shot Koa crater dimensions were enlarged because the device was emplaced in a water tank. The barge-shot craters were larger than values calculated from TM 23-200.

## *PREFACE*

The author wishes to acknowledge the assistance in the planning and execution of this project by the following people: Maj R. H. Myers; LCDR B. S. Merrill; J. G. Lewis; The Chief and members of the Special Projects Branch, ERDL, Fort Belvoir, Virginia; the Chief and members of the Blast Branch, Headquarters DASA; Lt Col J. W. Kodis, Lt F. E. Shoup, and C. Barnett, Program 1; and to Projects 1.7 and 1.8 for transient displacement and pressure measurements.

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# CONTENTS

FOREWORD	4
ABSTRACT	5
PREFACE	6
OBJECTIVES	9
BACKGROUND	9
THEORY	9
SHOT PARTICIPATION	13
DATA REQUIREMENTS	15
Aerial Photography	15
Topographic Survey	15
Fathometer Surveys	16
Miscellaneous Data	16
RESULTS	19
DISCUSSION	19
Crater Dimensions, Shot Cactus	19
Crater Dimensions, Shot Koa	22
Crater Dimensions, Shot Fig	31
Craters from Barge Shots	32
Crater Lip and Throwout	38
Depression Measurements	40
CONCLUSIONS	43
RECOMMENDATIONS	43
REFERENCES	43
TABLES	
1 Crater Radius Data	15
2 Site Yvonne Drilling Log, Station 181.03	19
3 Site Helen Drilling Log, Station 180.01	19
4 Site Helen Drilling Log, Station 180.02	20
5 Site Irene Drilling Log, Station 180.03	20
6 Crater Data, Land Shots	20
7 Crater Data, Barge Shots	20
8 Comparison of Barge Shot Craters with TM 23-200	21

9 Crater Lips -----	21
10 Surface Depressions -----	21

**FIGURES**

1 Crater radius versus height of burst, scaled to 1 kt -----	10
2 Crater depth versus height of burst, scaled to 1 kt -----	11
3 Adjusted crater radius versus yield -----	14
4 Eniwetok Lagoon stations -----	16
5 Depression marker, Station 170 -----	17
6 Depression marker, Station 171 -----	17
7 Shot Koa device placement -----	18
8 Shot Cactus device configuration -----	18
9 Shot Cactus preshot aerial photograph -----	23
10 Shot Cactus preshot photograph -----	23
11 Shot Cactus postshot aerial photograph -----	24
12 Shot Cactus postshot photograph -----	24
13 Shot Cactus postshot contours -----	25
14 Shot Cactus survey radii -----	26
15 Shot Cactus crater profile -----	26
16 Shot Koa preshot aerial photograph -----	27
17 Shot Koa postshot aerial photograph -----	27
18 Shot Koa survey radii -----	28
19 Shot Koa crater profile, Radii 1 and 4 -----	28
20 Shot Koa crater profile, Radii 2 and 5 -----	29
21 Shot Koa crater profile, Radii 3 and 6 -----	29
22 Shot Fig crater profile -----	31
23 Shot Linden survey radii -----	33
24 Shot Linden crater profile -----	33
25 Shot Oak survey radii -----	34
26 Shot Oak crater profile -----	34
27 Shot Yellowwood survey radii -----	35
28 Shot Yellowwood crater profile -----	35
29 Shot Butternut survey radii -----	36
30 Shot Butternut crater profile -----	36
31 Shot Holly survey radii -----	37
32 Shot Holly crater profile -----	37
33 Crater radius versus yield, barge shots -----	39
34 Crater depth versus yield, barge shots -----	39
35 Shot Cactus crater lip -----	41
36 Shot Cactus crater lip -----	41
37 Shot Cactus lip profile -----	42

# *PHYSICAL CHARACTERISTICS of CRATERS from NEAR-SURFACE NUCLEAR DETONATIONS*

## OBJECTIVES

The objectives of this project were to (1) measure the physical characteristics of the apparent craters and lips from near-surface nuclear detonations; (2) compare and correlate the data so obtained with those already available in order to more firmly establish the capability of predicting craters from surface-burst weapons; and (3) document the crater lip, throwout, and permanent vertical ground surface displacement surrounding the apparent craters.

## BACKGROUND

In the last several years, the increased interest in cratering as a primary damage mechanism has resulted in a need for data to improve crater-prediction techniques, particularly for surface detonations. Craters from twelve nuclear detonations in the EPG were documented during Operations Greenhouse, Ivy, Castle, and Redwing (References 1, 2, 3, and 4). Results have been analyzed and used in the prediction curve with factors given in TM 23-200 (Reference 5, Figures 2-20 through 2-26B).

Figures 1 and 2 of this report contain a summary of scaled crater data from past EPG operations as well as cratering curves taken from TM 23-200. The data show considerable scatter - which is due primarily to variation in soil structure of the islands, washing action of waves generated by the shots, and washing action by tidal effects. TM 23-200 suggests multiplication factors be used in conjunction with the TM dry-NTS-soil curves to account for these environmental conditions. In the theory section of this report, results from past EPG craters are compared with TM 23-200 by the use of factors.

In past operations, unusual weapon-tamping configuration has influenced the crater size (References 4 and 6). It would be impossible to assign crater adjustment factors for the many possible types of weapon-tamping configurations. One configuration that has not been fully evaluated is that in which a large water tank encloses a device, i. e., Shot Seminole, Operation Redwing (Reference 4). This configuration became important to this operation because Shot Koa had a similar tamping configuration. The crater formed from Shot Seminole was larger than expected, and this was attributed to the water enclosure. It was expected that Shot Koa would give additional information on this effect.

Reliable data on crater lip dimensions have been limited to a few high explosive cratering series and three nuclear craters. Lip dimensions for these shots have been taken from smoothed, average profiles representing actual lips of rough and irregular shapes. Several methods of predicting lip height are given in test literature; TM 23-200 indicates that the crater lip height is one-fourth of the crater depth, while other sources indicate scaling by fractional powers of the yield (Reference 7). Predictions of lip width have included areas large enough to contain all the large throwout fragments.

## THEORY

At the present time predictions of crater dimensions are based largely on empirical curves derived for the most part from data from high explosive charges supplemented by a few nuclear

detonations at the NTS and the EPG. These shots, however, were fired under a wide range of conditions; for example, variations of soil type, moisture content, and height or depth of burst (HOB). This complicated the correlation and enabled numerous curves to be drawn to fit plotted points without a sufficient number of points under one condition to make a statistical analysis or

to determine and understand deviations. A need, therefore, existed to collect all shot data and if possible reduce them to a standard condition, (i. e., soil, yield, and height of burst).

In order to reduce existing data to a standard condition it is recognized that many assumptions will have to be made and in many cases arbitrary factors used, especially on the data from the EPG. Much of this could be eliminated by high-explosive testing. Through a series of small high-explosive tests in homogeneous soils it might be possible to isolate certain soil properties

such as strength, saturation, and void ratio and to determine effects of these parameters on crater size.

In the absence of more refined testing, and for the purpose of more closely relating EPG data in this report, the following assumptions and factoring systems will be used.

The assumed standard conditions are: (1) homogeneous dry sandy soil; (2) zero height of burst; i. e., the center of gravity of the charge at the ground surface with the lower part of the charge in full contact with the cratering medium; (3) spherical charge; and (4) 1-kt yield.

Scaling for crater radius is based on cube root scaling; i. e., the radius varies directly as the cube root of the yield (or charge weight)

$$R = AW^{1/3} \text{ for scaled HOB}$$

Where: R = radius in feet

W = yield in kt

A = constant

This is a straight line with a slope of one third when plotted on log paper; i. e.,  $\log R = \log A + \frac{1}{3} \log W$  with A the intercept for a yield of 1 kt at the surface.

Although deviations from cube root scaling may exist for variations in yield and height of burst, cube root scaling is assumed to hold for all materials (sand, clay, rock), conditions of materials (saturation, compaction), and heights of burst, then only the intercept (A) will be changed with a change in materials or height of burst, and a family of lines which are parallel to the standard line will exist. It becomes necessary to introduce factors by which the intercept (A) can be modified in order to reduce all data to the standard line: Thus  $R = f(F_1, F_2, \dots, F_n) AW^{1/3}$ . Since the precise nature of the function is not known, it will be assumed as  $R = F_1 F_2 \dots F_n AW^{1/3}$ .

There remains the problem of finding the variables, defining them with known tests and relating them to the crater radius. It is assumed that the values of these factors can be determined independently of each other.

Since no new high-explosive test data are available for determining these variables, TM 23-200 and past test data will be used as a guide. These variables are defined in the TM by three gross factors as follows:

<u>Soil Type</u>	<u>Factors</u>
Saturated soil	1.5
Washed soil	2
Granite or Sandstone	0.8
Sand	1.0

The above factors may be a guide to the limits by which craters are affected by these variables. If a more detailed analysis of the soil is made other variables such as void ratio, soil fracture in the crater vicinity, and degree of confinement can be used toward a greater accuracy in crater prediction.

Until further determinations are made as to standard soil conditions, the dry soil curve as given in TM 23-200 shall serve as the standard curve, and the value of A shall be taken as 64 feet.

With the exception of height of burst, energy containment, and washing, all variables are directly concerned with soil properties.

The HOB factor,  $F_1$ , is determined from the standard dry soil curve contained in TM 23-200. This curve, Figure 1, shows a change in crater radius as the burst position of the device varies from the ground surface. A factor for any scaled height of burst is found by determining the factor needed to adjust the crater radius to that of a surface burst. The accuracy of such factors would depend upon the accuracy of the TM 23-200 curve and scaling. Adjusting and comparing of craters with scaled height of burst above 20 feet by means of HOB factors is not considered necessary since these craters are only shallow ground depressions.

The  $F_2$  factor may be denoted as a strength factor and is probably related to the strength of the soil in compression and shear. The relationship should be sought in terms of the unconfined compressive strength since the appropriate degree of confinement is not constant, sand cannot be tested for compression in an unconfined condition, therefore, it shall be given a strength factor of one. The upper limit, then, for the  $F_2$  factor is 1.0. The lower limit would be the value for hard rock, which for granite, as given in the TM, is approximately 0.8.

The  $F_3$  factor accounts for degree of saturation. (The degree of saturation is the percentage of voids which are filled with water and ranges from 0.0 for a dry sand to 100.0 for a completely saturated soil.) Since dry sand is the standard having a value of 1.0 the lower limit would be 1.0. The upper limit, representing complete saturation, will vary for sand or clay type soils but to be consistent with TM 23-200 a value of 1.5 will be used.

The  $F_4$  factor is for washing and ranges from 1.0 to 1.33 for saturated sand. Clay type soils are expected to be affected to a lesser degree by washing, and rock is expected to be affected to a still lesser degree. It is recognized that craters at the EPG have been subjected to different degrees of washing as evidenced by the existence of crater lips for some craters. An attempt will be made to assign factors for (1) complete washing to craters with no lips, (2) partial washing to craters where evidence of lip exists, and (3) no washing for craters with lips that are land locked.

Another factor,  $F_5$ , energy containment, can be entered into the equation. This factor will be a correction for the degree of containment of the nuclear device which results in the directing of more or less energy into the ground. This is a significant factor since data from two contained surface shots (Shots Seminole and Koa) in the EPG area indicate a considerable increase in crater dimensions with some form of tamping. A number of variables such as density and thickness of containment material, weapon design, and placement all enter into the determination of this factor. It is probable that each detonation of this nature must be analyzed separately.

Another factor,  $F_6$ , can be inserted for inhomogeneities that are relatively distant in comparison to the close-in phenomena. That is, this inhomogeneity factor is a correction for such

changes in the media as interfaces and cavities. Here again each shot must be studied individually. This factor has more effect on crater depth and profile than radius according to data from a high-explosive test, Reference 8.

The above analysis has been for the determination of crater radius. Crater depth, it is felt, is a function of the same variables though numerical values of  $F_1$  through  $F_4$  may be different for crater radius and depth. The problem now becomes one of reconsidering the individual shots at the EPG and by assuming adjustment factors, using the above discussion as a guide, making a better correlation of the crater data.

Ivy Mike was a 10.5 Mt device fired at a height of burst of 35 feet. Crater measurements show a radius of 2,810 feet and a depth of 120 feet. Crater pictures show an absence of any lip; a condition which indicates full washing. In using a factoring system to reduce the crater to NTS conditions, the radius should be reduced by a factor of two to account for saturation and washing but increased by a factor of  $1/0.94$  to compensate for height of burst. The adjusted radius would be approximately 1,500 feet.

Castle Shot 1 was a 14.5 Mt device fired at a height of burst of 15.5 feet. Crater measurements showed a radius of 3,000 feet and a depth of 240 feet. This shot was also considered to be fully washed. A factor of two is, therefore, used for saturation and washing effects. The HOB factor in this case would be  $1/0.98$  and the adjusted radius would be approximately 1,530 feet.

Castle Shot 3 was a 110 kt device with a 13.6 foot height of burst. The portion of the island in which the crater was formed had a steep slope into the lagoon. The crater radius on the island side ranged from 380 to 410 feet. The radius on the lagoon side was in excess of 600 feet and indicated a possible venting of cratering energy in this direction. An average radius of 460 feet does not seem improbable. The crater had a broken and irregular lip with an average height of 10 feet on the island side indicating that the crater was not completely washed from the wave action generated by the explosion. Since it is assumed that complete washing did not take place, a washing and saturation factor of only 1.8 instead of 2 should be used. The HOB factor in this case would be  $1/0.84$ . The adjusted radius would then be approximately 300 feet.

Shot Lacrosse was a 39.5 kt device with a height of burst of 17 feet. The radius was 202 feet. This crater was completely land locked and was not considered washed. The soil in this area consisted of some cemented sand and coral. Since it was more cohesive than NTS soil, it should have exhibited greater compressive strength. Therefore, a soil strength factor of  $1/0.9$  is used. Since the soil was fully saturated, at high tide the water covered ground zero, a saturation factor of 1.5 is used. The HOB factor is  $1/0.7$  and the adjusted radius would be approximately 215 feet. If a saturation factor of 1.4 instead of 1.5 is used as suggested in WT-1307 the adjusted radius is 230 feet. Both values are plotted in Figure 3.

The Shot Seminole device is discussed later with reference to the Shot Koa crater. The Seminole radius due to its protected position and lip condition should be increased by about 20 percent in order to be fully washed. A saturation-washing factor of two can then be used. Due to the water tamping and near-surface placement this shot was considered to be a surface burst and an HOB factor was not needed. An energy containment factor of 30 percent for the water tank emplacement was found by comparing the adjusted radius of 198 feet to that from a surface burst, or 152 feet. The adjusted radius for the 13.5 kt Seminole device would be 152 feet.

The straight line in Figure 3 was drawn using the intercept given in TM 23-200 of 64 feet and one third slope. The plotted points represent EPG data adjusted to surface detonations in dry soil as given above. Table 1 gives adjusted and unadjusted crater radii for EPG shots including Shots Cactus and Koa.

#### SHOT PARTICIPATION

Shots Koa, Cactus, and Fig, the only land-surface shots of Operation Hardtack, constituted the primary participation of this project. Limited participation was carried out on barge shots Linden, Oak, Yellowwood, Butternut, and Holly.

## DATA REQUIREMENTS

Data requirements consisted of (1) preshot and postshot aerial photographs provided by Program 9; (2) topographic surveys, provided by Holmes and Narver; (3) fathometer soundings of underwater craters, provided by Holmes and Narver; and (4) miscellaneous information, such as device-shielding configuration and drilling logs. Figure 4 is a sketch of Eniwetok Atoll showing shot locations.

Aerial Photography. Preshot and postshot aerial photographs were taken of Shots Cactus, Koa, Fig, and Nutmeg. An RB-50E aircraft, equipped with a gyro stabilized T-11 camera with 6-inch focal length, was used to make the mapping runs. The intervalometer was set for a forward overlap of 57 to 62 percent. Calibration certificates are on file at Engineer Research and Development Laboratories (USAERDL) for all T-11 cameras, precluding the necessity of special calibration runs. A predetermined altitude was maintained by a radio altimeter, FCR 718. This instrument can indicate altitudes between 200 and 60,000 feet with an accuracy of  $\pm 25$  feet over smooth terrain.

The film was developed at EPG to insure proper coverage of the target and then sent to Fort Belvoir for photogrammetric analysis. The accuracy of the stereographic data was limited by

TABLE 1 CRATER RADIUS DATA

Shot	Yield	Crater Radius	Adjusted Crater Radius
Ivy Mike	10.5 Mt	2,810	1,500
Castle 1	14.5 Mt	3,000	1,530
Castle 3	110 kt	500	300
Lacrosse	39.5 kt	202	215
Seminole	13.5 kt	330	152
Cactus	17 kt	170	133
Koa	1.38 Mt	2,000	770
Fig			

the deviation of the altimeter reading from the true value, since the error of the equipment was negligible by comparison.

Topographic Survey. A preshot and postshot horizontal and vertical survey of ground zero was made for Shots Cactus, Koa and Fig. These measurements were made by transit on land and by lead-line soundings underwater. The craters of Shots Cactus and Koa were large enough so that random measurements would not have sufficiently described the crater profile. Measurements, therefore, were made along 6 radii which were approximately 60 degrees apart, extending from ground zero out to 500 feet for Shot Cactus and from ground zero to 2,500 feet for Shot Koa.

Zero elevations on all surveys have been taken as the datum plane on which tide tables are based: 0.5 feet below mean low-water spring tide.

The vertical and horizontal controls were of a third order triangulation and ordinary leveling.

Detailed crater measurements of Shots Cactus and Koa could not be made until radiation levels were low enough to permit the safe re-entry of survey crews. A depth sounding from helicopters, therefore, was planned for the Shot Cactus crater on shot day before crater changes due to later washing could take place. A practice sounding was made on a similar crater, Shot Lacrosse, and the depth at ground zero was found to have changed only 4 feet in 2 years. The early sounding was, therefore, delayed until radiation levels had decayed to about 1 r/hr.

Since the Shot Koa crater was expected to breach to open water on three sides, it was felt that an early depth sounding was also necessary. This sounding was made from a boat on D+4 since a boat can enter a breached crater earlier than a helicopter, due to lower radiation levels

near the water surface. Due to rough water and the difficulty of locating ground zero the depth was measured only 135 feet as compared to the later more detailed soundings of 170 feet.

Depression measurements of the ground surface were made by preshot and postshot surveys of heavy concrete gage pads used by Projects 1.7 and 1.8. Figures 5 and 6 show the types of

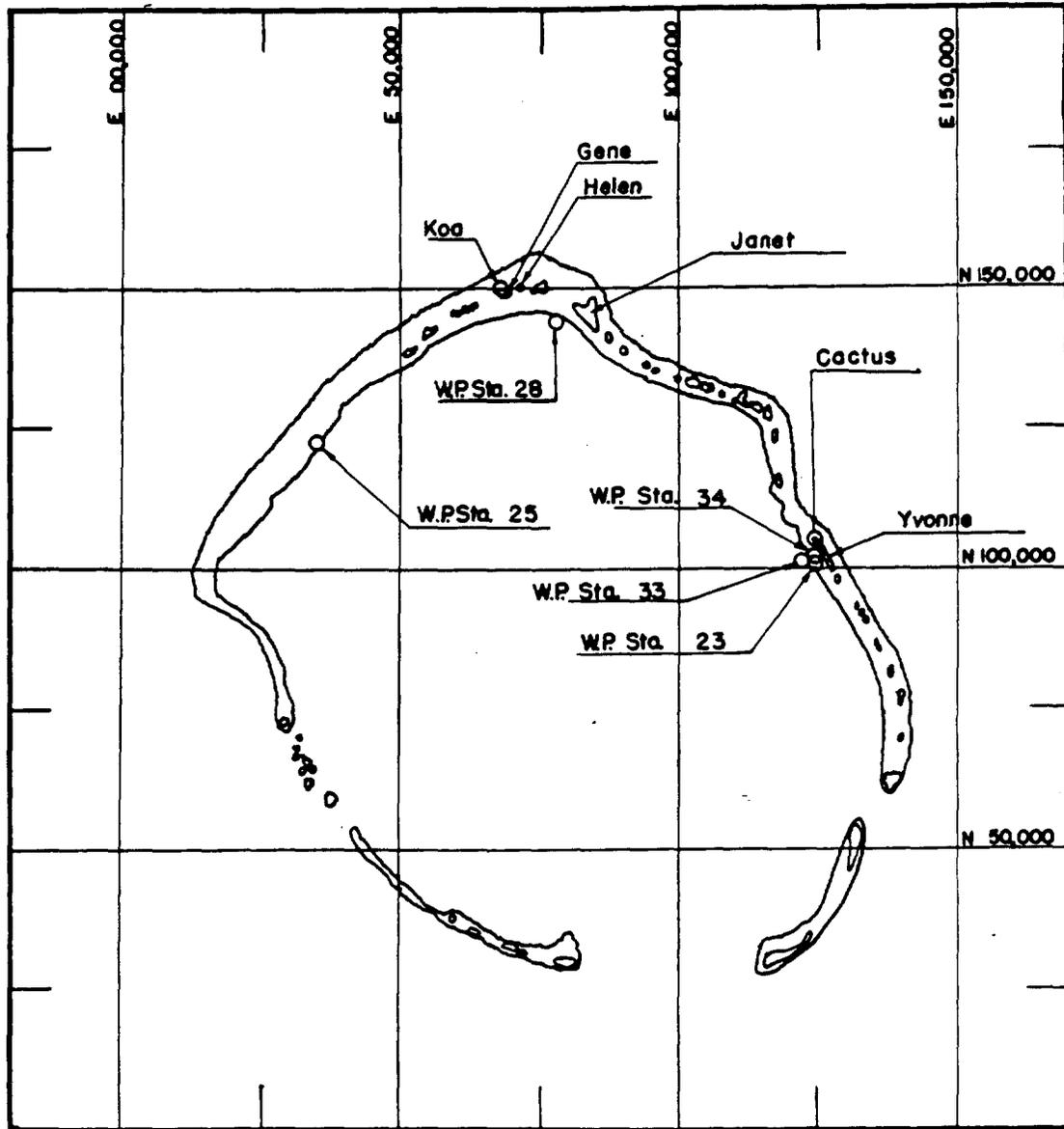


Figure 4 Eniwetok Lagoon stations.

concrete pads used by Project 1.7. The 171 station pads extended from the ground surface to a depth of 4 feet. The pads of Project 1.8 extended to a depth of 1 foot.

Fathometer Surveys. Holmes and Narver Company, as part of their normal operations, conducted fathometer surveys of all barge shots expected to have an underwater crater. Shots from which crater data were available were Shots Linden, Oak, Yellowwood, Butternut, and Holly.

Miscellaneous Data. Tamping configurations of Shots Koa and Cactus are shown in Figures 7 and 8. The inner tank of the Shot Koa configuration was an air space in which the device was

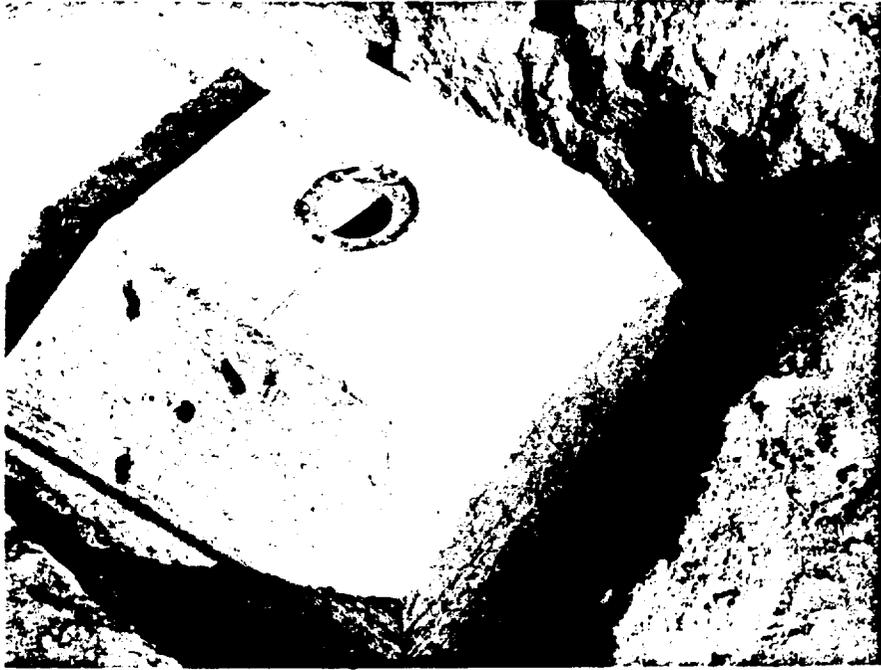


Figure 5 Depression marker, Station 170.

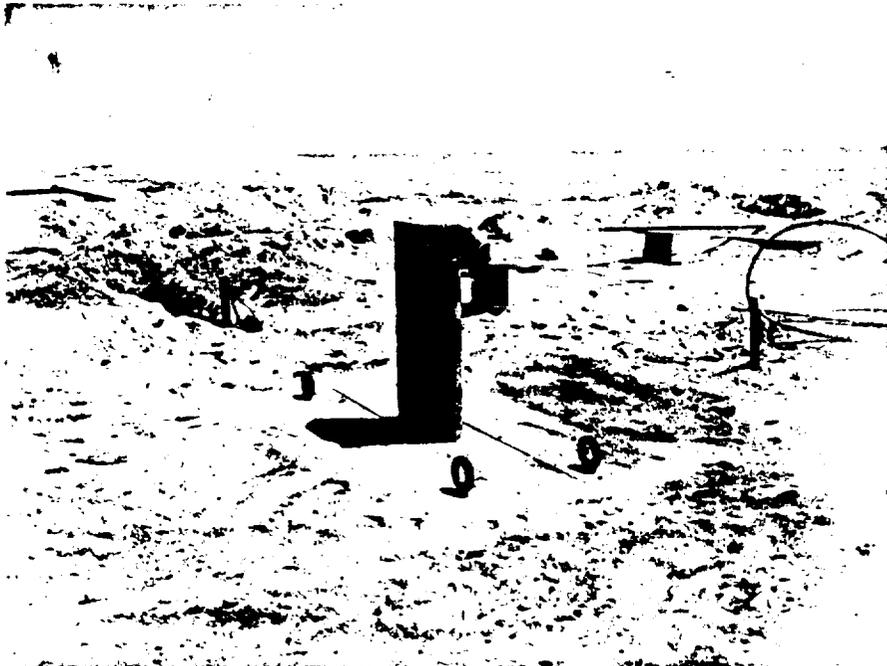


Figure 6 Depression marker, Station 171.

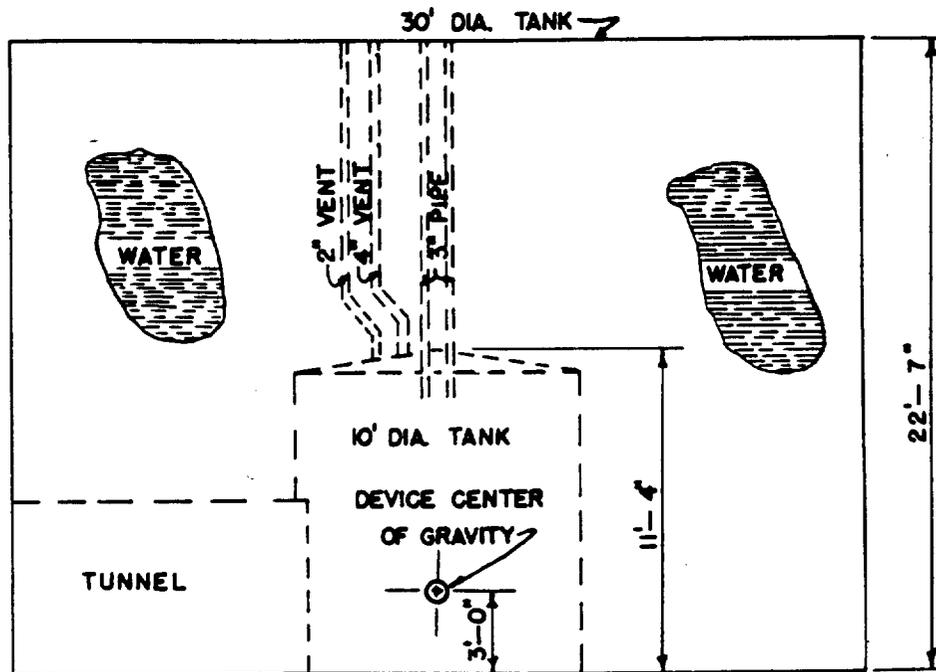


Figure 7 Shot Koa device placement.

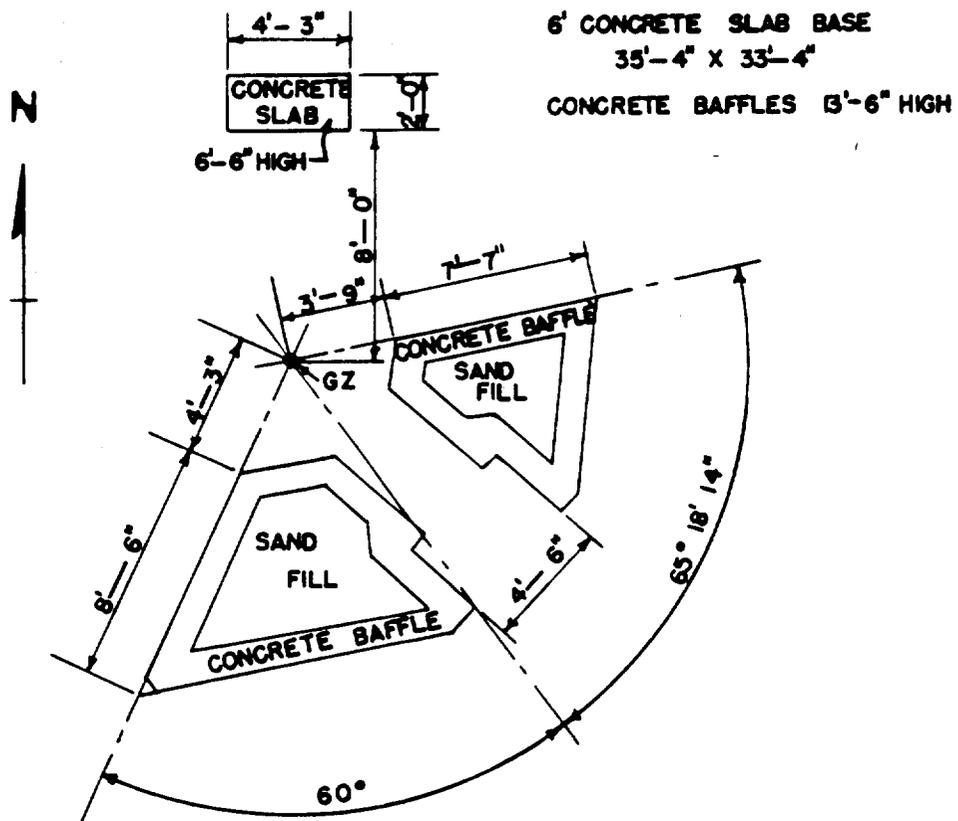


Figure 8 Shot Cactus device configuration.

located. The outer tank was filled with water. The volume of water surrounding the device was about  $1.5 \times 10^4 \text{ ft}^3$ , corresponding to a mass of  $9.6 \times 10^5$  pounds.

Results of drilling logs for Sites Yvonne, Helen and Irene are shown in Tables 2, 3, 4, and 5. These logs were the best available information of the nature of the soil conditions in which

TABLE 2 SITE YVONNE DRILLING LOG, STATION 181.03

Coordinates: North, 105,618.17; East, 124,611.56.

Depth, ft	Description
1 to 8	Soft sand.
8 to 16	Hard cemented sand.
16 to 23	Soft cemented coarse sand with hard layers.
23 to 32	Soft cemented sands with shells.
32 to 45	Soft cemented sands with shells and hard layers.
45 to 50	Hard cemented sands with shells.
50 to 58	Hard cemented sands with shells.
58 to 62	Soft cemented sands with hard layers.
62 to 72	Soft cemented sands and shells.
72 to 108	Soft cemented sands and shells with hard layers.

the Cactus and Koa craters were produced. Additional information on soils in the EPG area can be found in References 1 and 4. Seismic measurements were made on Sites Yvonne and Irene by Project 1.8 and are discussed in Reference 9.

## RESULTS

Data presented in this report are divided into crater dimensions from land shots, Table 6; crater dimensions from barge shots, Tables 7 and 8; lip dimensions, Table 9; and ground depression measurements, Table 10.

## DISCUSSION

The influence of soil characteristics and wave action on crater dimensions has been developed and discussed in the background and theory section. The following discussion points out their

TABLE 3 SITE HELEN DRILLING LOG, STATION 180.01

Coordinates: North, 149,360.00; East, 73,120.00

Depth, ft	Description
1 to 10	Sand.
10 to 20	Cemented soft sand.
20 to 30	Cemented rubble, medium hard.
30 to 50	Cemented rubble, soft.
50 to 70	Cemented rubble and shells.
70 to 80	Cemented shells, soft.
80 to 108	Cemented rubble, soft.

apparent effect on the craters measured during this operation and through adjustments compares the results with the curves given in TM 23-200. Scaled dimensions listed in this report, unless otherwise specified, are scaled to 1 kt of nuclear yield.

Crater Dimensions, Shot Cactus. The Cactus device was detonated on the northwest end of Site Yvonne near the Shot Lacrosse crater and like Lacrosse was considered to be an unwashed

TABLE 4 SITE HELEN DRILLING LOG, STATION 180.02

Coordinates: North, 149,507.11; East, 74,247.25

Depth, ft	Description
1 to 10	Fill sand.
10 to 15	Hard coral.
15 to 20	Hard coral with black coral.
20 to 25	Cemented rubble with black coral.
25 to 35	Hard coral with black coral.
35 to 40	Cemented rubble.
40 to 50	Cemented rubble with shells.
50 to 90	Cemented sand with rubble.
90 to 108	Cemented rubble with shells.

TABLE 5 SITE IRENE DRILLING LOG, STATION 180.03

Coordinates: North, 150,329.74; East, 74,949.11.

Depth, ft	Description
1 to 10	Soft powdered sand to soft sand.
10 to 20	Soft sand and shells.
20 to 40	Soft rubble and sand.
40 to 60	Cemented rubble.
60 to 80	Cemented rubble and sand.
80 to 108	Cemented sand and shells.

TABLE 6 CRATER DATA, LAND SHOTS

All dimensions are in feet.

Parameter	Koa	Cactus	Fig
Radius (R)	2,000	170	
Depth (D)	171	34.5	
Height of Burst (HOB)	3	3	
Yield (W)	1.38 Mt	17 kt	
Dimensions scaled to 1 kt:			
R/W <sup>1/3</sup>	179	66.2	
D/W <sup>1/4</sup>	28.5	17	
D/W <sup>1/3</sup>	15.3	13.4	
HOB/W <sup>1/3</sup>	0.27	1.16	

TABLE 7 CRATER DATA, BARGE SHOTS

All dimensions are in feet.

Parameter	Lunden	Oak	Yellowwood	Butternut	Holly
Radius (R)		2,200			
Depth (D)		183			
Yield (W)		8.9 Mt			
Height of Burst above Water (H)		6.5			
Depth of Water (h)		13			
Dimensions scaled to 1 kt:					
R/W <sup>1/3</sup>		106			
D/W <sup>1/4</sup>		18.8			
H/W <sup>1/3</sup>		0.314			
h/W <sup>1/3</sup>		0.63			

TABLE 8 COMPARISON OF BARGE SHOT CRATERS WITH TM 23-200

Shot	Actual	TM 23-200	Actual	TM 23-200	Percent Deviation of Radius	Percent Deviation of Depth
	Radius	Radius	Depth	Depth		
	ft	ft	ft	ft		
Linden						
Oak	2,200	1,900	183	150	16	-3.5
Yellowwood						
Butternut						
Holly						

TABLE 9 CRATER LIPS

All dimensions are in feet.

Parameter	Koa	Cactus	Fig
Lip Height	0	8 to 14	
Lip Width	0	115 to 170	

TABLE 10 SURFACE DEPRESSIONS

Station	Shot	Coordinates		Distance from Ground Zero	Depression
		North	East		
				ft	ft
181.01	Cactus	105,982.12	124,347.85	410	Nothing found
170.05		105,938.88	124,402.25	470	Nothing found
170.06		105,880.99	124,444.07	540	Nothing found
170.07B		105,795.39	124,368.15	595	Nothing found
170.08		105,793.28	124,492.96	640	Nothing found
171.04		105,799.17	124,504.32	640	Nothing found
181.02		105,782.28	124,492.65	650	Nothing found
174.11		105,684.74	124,587.58	780	Nothing found
181.03		105,618.17	124,611.56	850	0.06
171.05		105,523.46	124,708.82	980	0.09
174.17	105,340.22	124,773.79	1,171	Nothing found	
170.01	Koa	149,089.49	72,646.21	1,550	Nothing found
180.01		149,360.00	73,120.00	2,000	Nothing found
170.02		149,391.28	73,519.79	2,400	Nothing found
170.03		149,545.85	74,082.19	2,968	Nothing found
180.02		149,490.45	74,243.18	3,131	0.38
170.04		149,466.82	74,352.23	3,234	2.0
180.03		150,313.31	74,953.74	3,950	-0.35
175.01		150,599.91	74,873.86	3,953	Nothing found
176.02	150,442.48	75,456.95	4,470	Nothing found	
174.05	150,559.08	75,434.93	4,478	Nothing found	
175.02	150,559.08	75,434.93	4,478	Nothing found	
174.08	150,085.54	76,587.11	5,515	Nothing found	
1131	Cactus	Cement supports of pipeline from ground zero to Station 1131		306.7	0.26
				336.6	0.18
				366.6	0.72
				396.6	0.46
				421.2	1.05
				447.3	1.75
	467.5	1.19			

crater. It is felt that the water waves generated by the shot were insignificant since the water over the reef was only a few feet deep. Photographs show that the Cactus crater was filled with water but essentially unwashed. Preshot and postshot photographs are shown in Figures 9, 10, 11, and 12.

The measured crater radius of 170 feet and depth of 34.5 feet were obtained from photogrammetric measurements, Figure 13, and from lead-line soundings. The profile, Figure 15, was plotted from preshot and postshot survey data and lead-line soundings along 6 radii, Figure 14. The photogrammetric measurements were made from aerial photographs.

To compare these crater dimensions with those from the dry soil curves of TM 23-200, it was necessary to obtain factors for adjusting the Shot Cactus dimensions. This can be done by comparing Shot Cactus and NTS environments (soil strength and moisture condition).

The soil at Site Yvonne is interspersed with layers of hard and soft cemented sand, coral, and shells, and is considered to be more cohesive than the NTS soil. Tests conducted under Project 1.8 indicated that cementation at Site Yvonne was much more complete than at Site Irene and, therefore, less crushing would be expected at high stress levels. Drilling logs were made from holes drilled 400 feet southeast of ground zero; results are presented in Table 2.

In order to adjust the crater radius for soil strength, an  $F_2$  factor value of 0.9 is arbitrarily assumed because, as stated above, the Site Yvonne soil is more cohesive than NTS soil, upon which the dry soil curve was based, but not as hard as granite (for which a factor of 0.8 is given).

Soil moisture conditions, although slightly different from those existing at the Shot Lacrosse site, are assumed to be fully saturated for the purpose of these calculations, and a saturation factor of 1.5 is used. The adjusted scaled crater radius is 48.3 feet. The radius given in TM 23-200 for the same crater under NTS conditions is 60 feet. If Shot Cactus height of burst were adjusted to a surface burst by using an HOB factor, the corrected radius would be 51.5 feet to 64 feet given in the TM or a difference of approximately 24 percent. This percentage is well within the accuracy of the basic TM curve. It is probable, however, that a factor of 1.4 instead of 1.5 should have been used as the saturation factor since the top few feet of the soil around ground zero was above the water table and was essentially in a dry state. If this were the case, then the scaled adjusted radius would have been 59 feet giving a difference of only 10 percent of the listed value of 64 feet. Both values are plotted in Figure 3.

The adjusted crater depth was more a matter of conjecture but it was felt that the underlying formations, acting as interfaces, decreased the depth considerably. The relative flatness of the crater bottom and the steep sides tended to support this theory. Similar craters were formed from high-explosive detonations in soils having cement interfaces at various depths, Reference 8. The Cactus crater depth was predicted by using data from Shot Lacrosse which had a depth of only 44 feet. The drilling log also shows a hard cemented interface at approximately this depth. The depth of a crater in saturated soil would normally be predicted as 1.5 times the value in dry sand, as taken from TM 23-200.

Crater Dimensions, Shot Koa. The Shot Koa device was detonated inside a 30-foot-diameter water tank on the west end of Site Gene at the edge of the Ivy Mike crater. A preshot photograph with a line indicating the crater edge is shown in Figure 16. A postshot picture of the crater edge is shown in Figure 17. Station 360.01 can be identified in both photographs.

Preshot and postshot survey radii are shown in Figure 18. The postshot radii are displaced from the preshot by a distance of 208 feet, making it difficult to relate the preshot overburden to the postshot crater. To better define the crater the lead-line soundings along the postshot radii have been shifted 208 feet to correspond with preshot data and plotted as profiles, Figures 19, 20, and 21. This procedure introduces some error, particularly insofar as depth measurements are concerned; however, the error is slight and no reasonable basis for correction exists. Radii 1 and 4 pass through ground zero and show the true measured crater depth.

A crater radius of 1,825 feet was given in the ITR and was found by measuring the distance from ground zero to Station 360.01, which was within 5 feet of the crater edge. A more accurate measurement of the crater profiles would give a radius of slightly in excess of 2,000 feet.



Figure 9 Shot Cactus preshot aerial photograph.

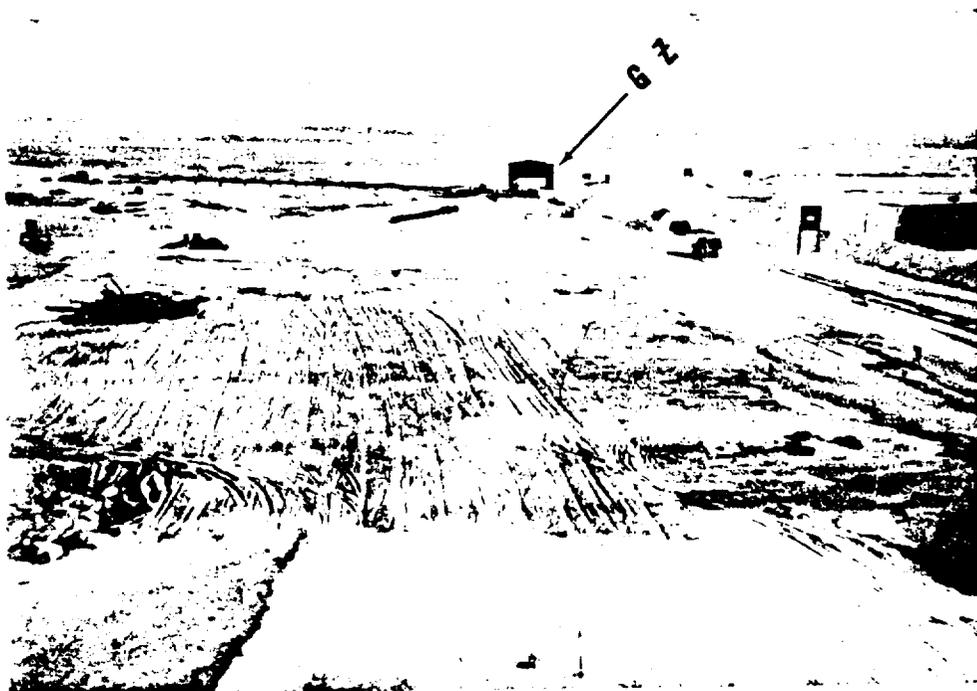


Figure 10 Shot Cactus preshot photograph.



Figure 11 Shot Cactus postshot aerial photograph.



Figure 12 Shot Cactus postshot photograph.

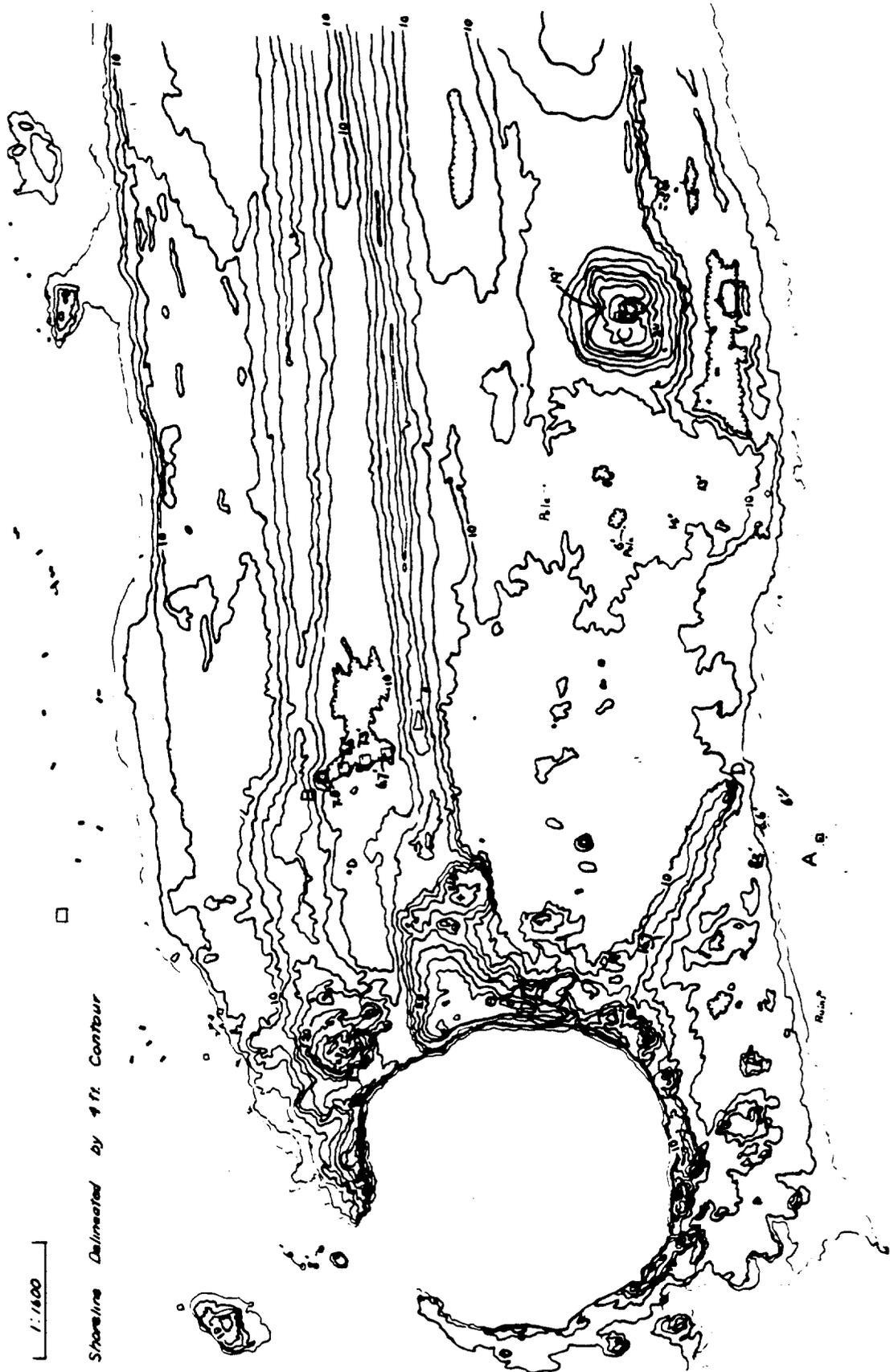


Figure 13 Shot Cactus postshot contours.

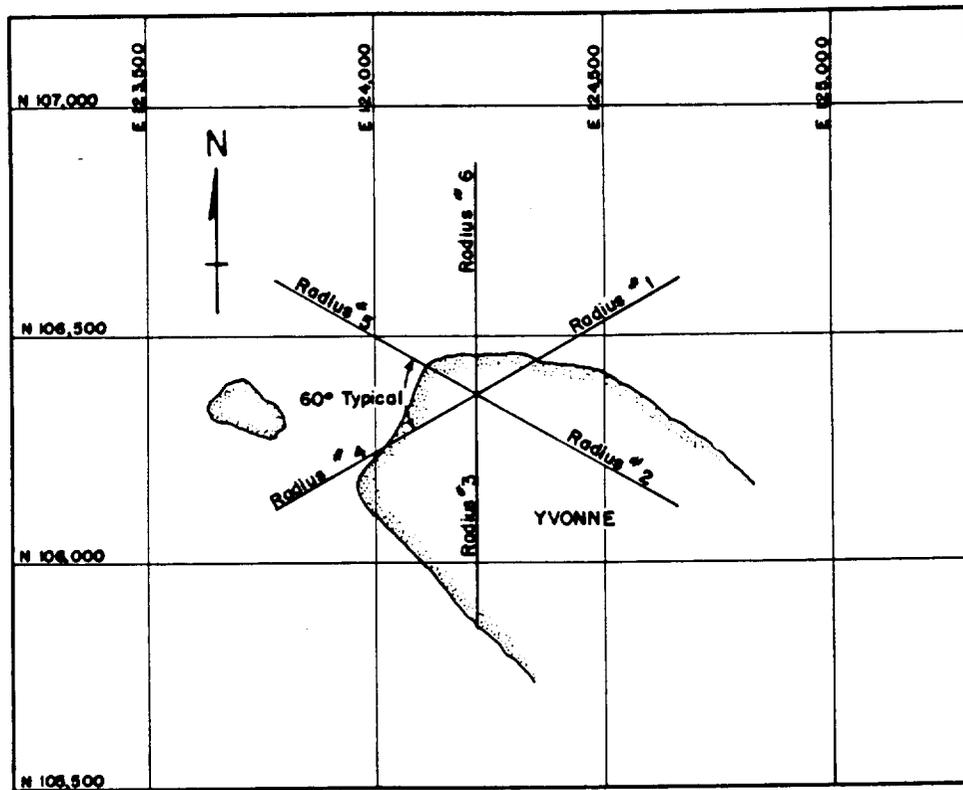


Figure 14 Shot Cactus survey radii.

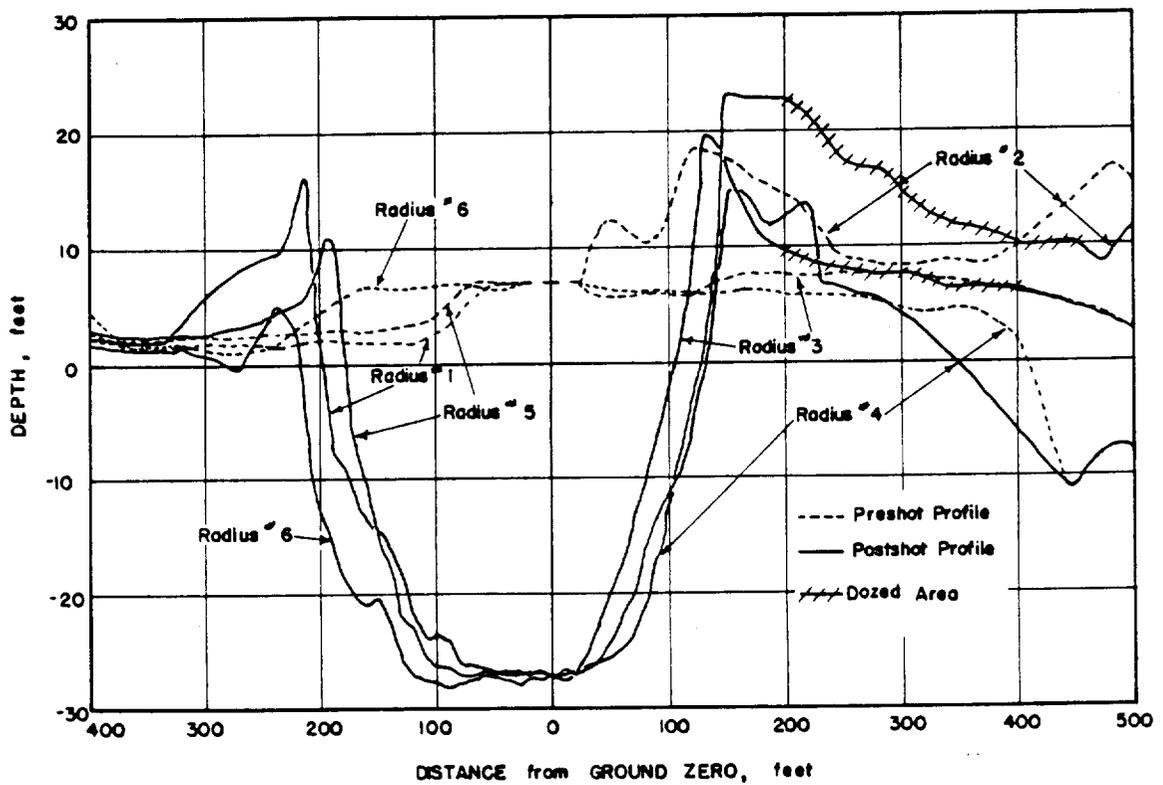


Figure 15 Shot Cactus crater profile.

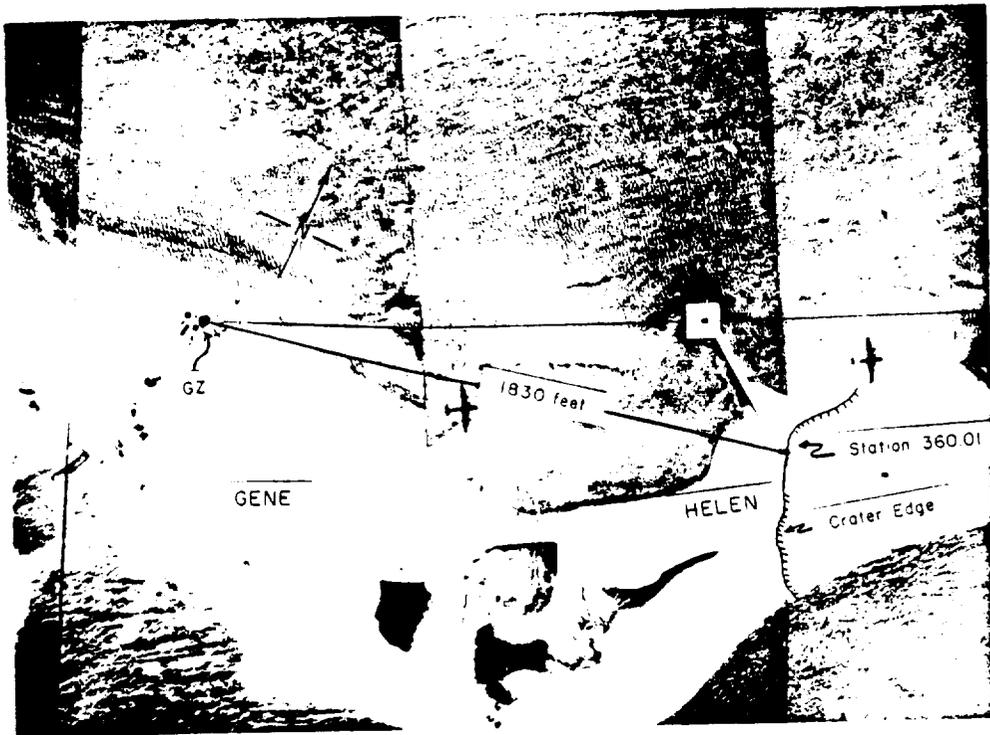


Figure 16 Shot Koa preshot aerial photograph.

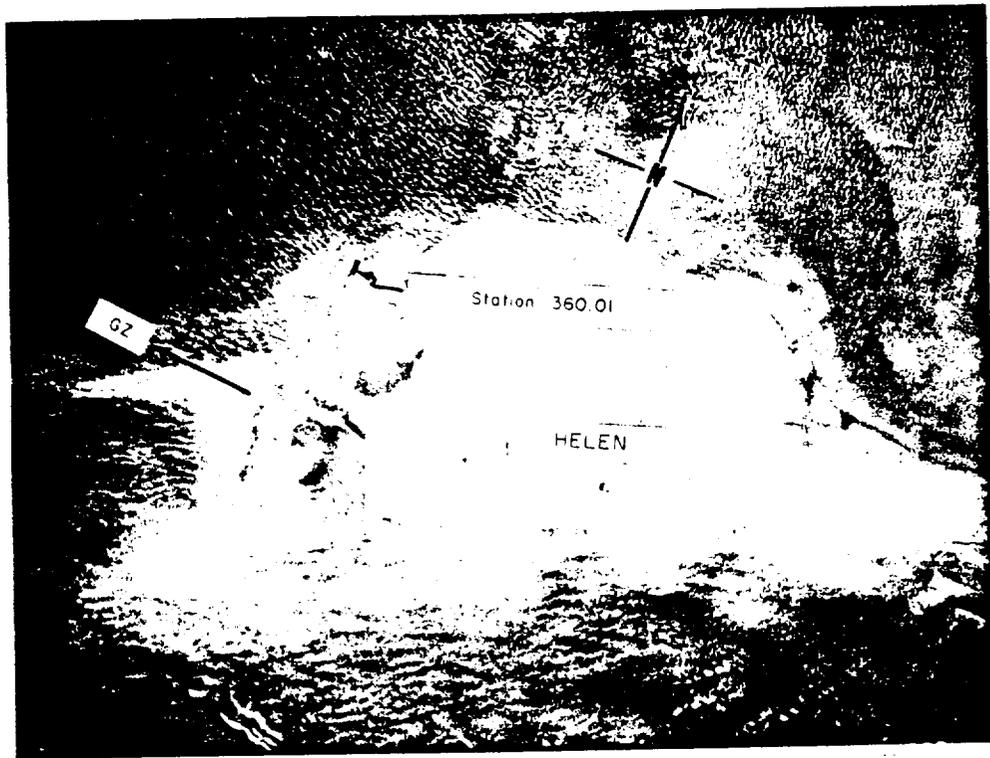


Figure 17 Shot Koa postshot aerial photograph.

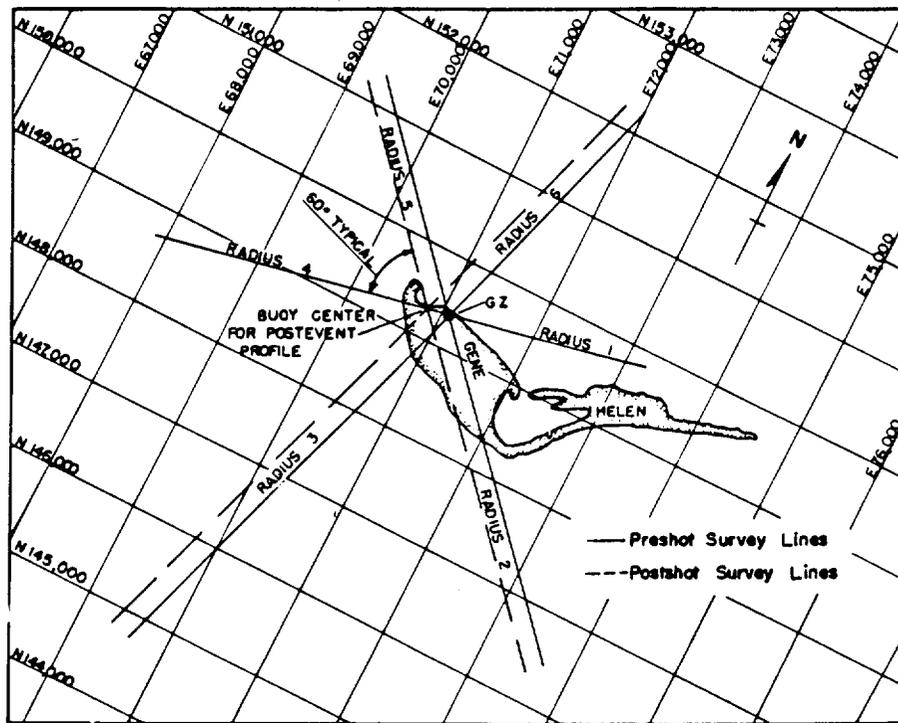


Figure 18 Shot Koa survey radii.

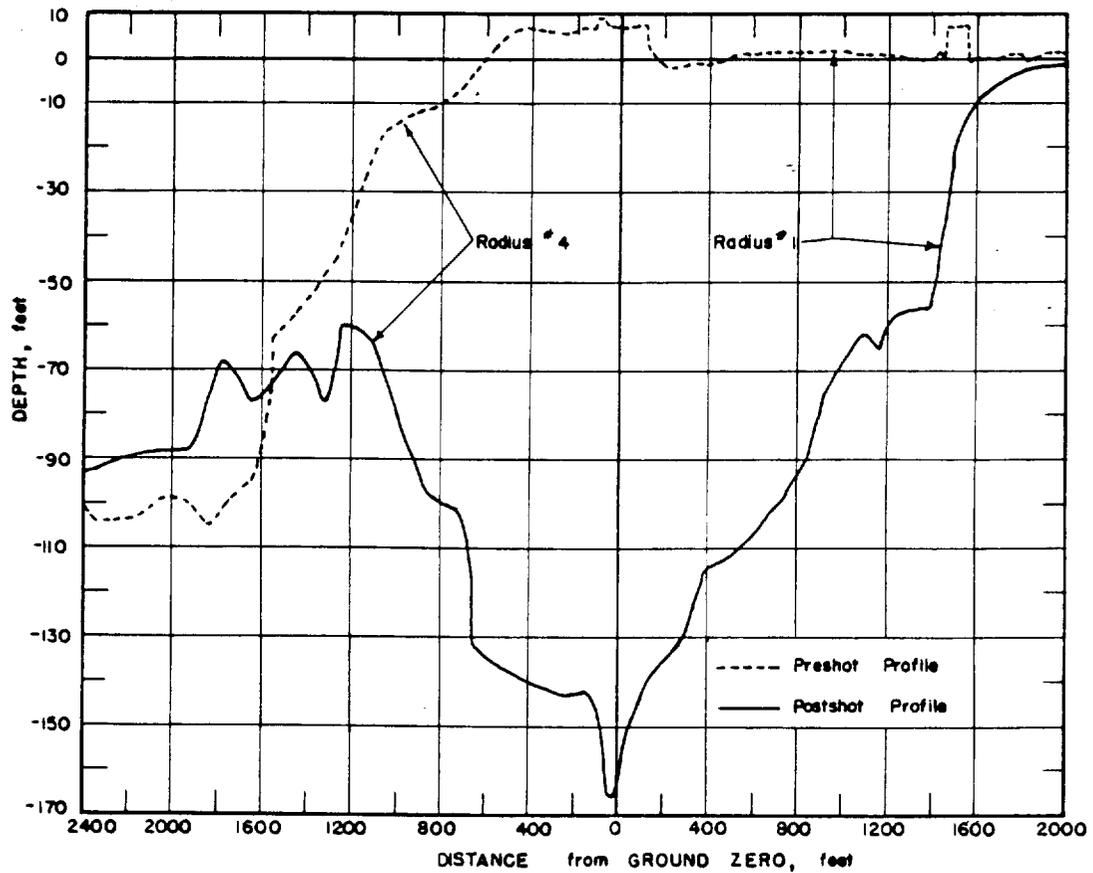


Figure 19 Shot Koa crater profile, Radii 1 and 4.

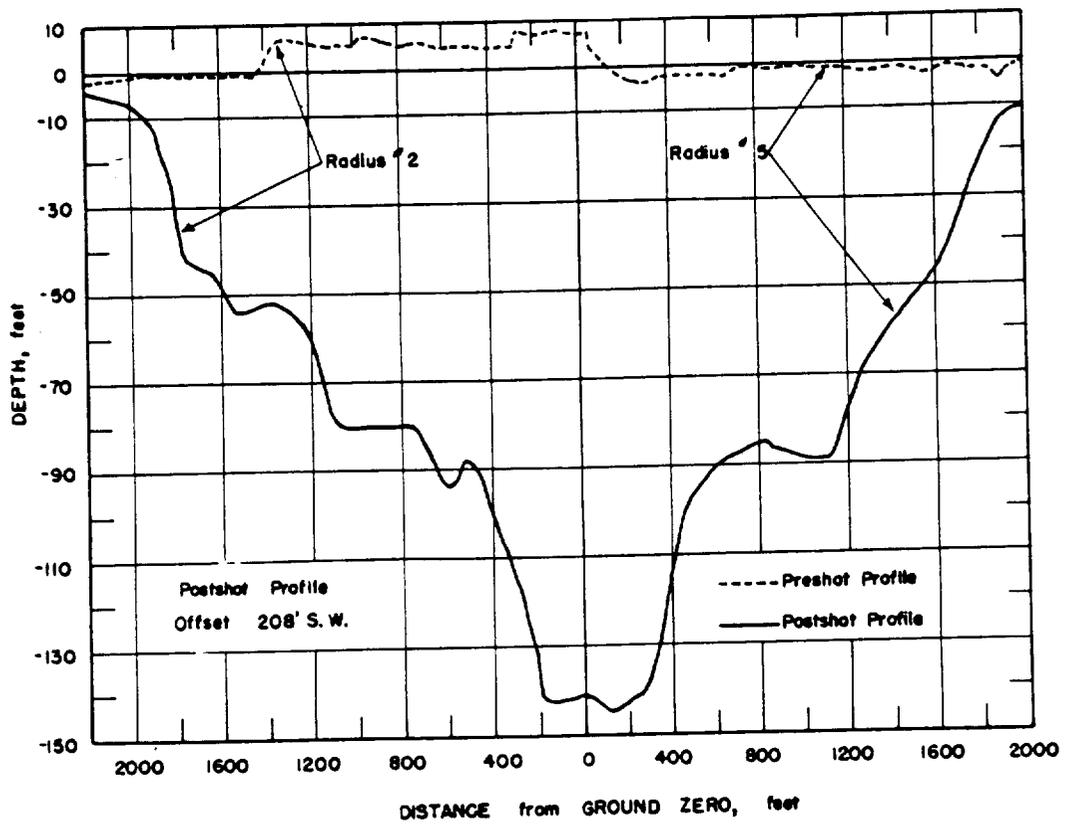


Figure 20 Shot Koa crater profile, Radii 2 and 5.

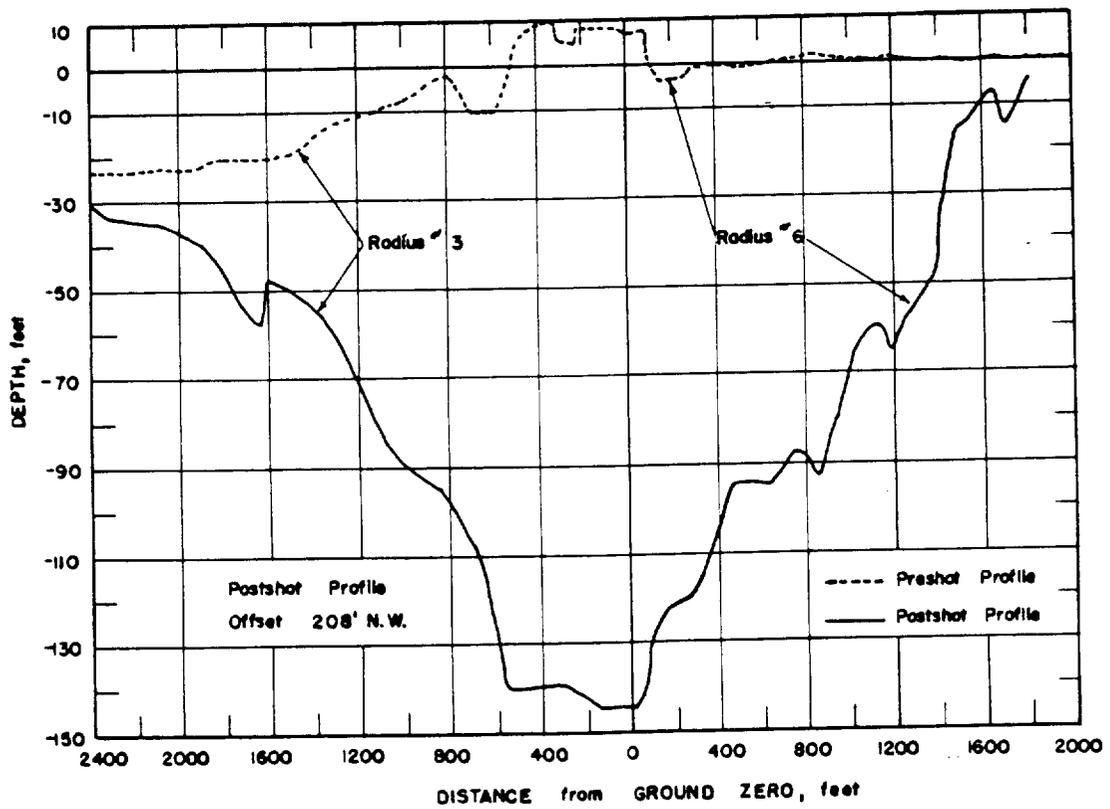


Figure 21 Shot Koa crater profile, Radii 3 and 6.

Crater depth as shown in the profile is 171 feet, Figure 19. It should be pointed out that the data is taken from lead-line soundings since fathometer surveys of this crater 4 days after shot time indicated a depth of only 81 feet. The difference between lead-line and fathometer surveys was presumably due to a suspension of mud and silt in the crater.

The scaled crater radius of 179 feet for an actual radius of 2,000 feet, or at the most conservative estimate, 164 feet for a radius of 1,825 feet, is the largest measured scaled radius from a land surface shot. Using a washing factor of two and considering Shot Koa to be a normal surface burst the scaled radius value calculated from TM 23-200 would have been only 128 feet or a factor of 30 to 40 percent lower than the actual value. The scaled crater depth of Shot Koa was 28.5 feet. The scaled depth value obtained using the TM dry soil curves and a washing factor of 0.7 was only 14 feet.

Soil information obtained at Sites Gene and Helen, indicated soft sand with fractured underlying lens of cemented sand. The fractured condition may be partly due to the shattering effect of the nearby Ivy Mike and Operation Redwing Shot Seminole shots. During past operations large, waterfilled voids were found in the soil underlying Sites Gene and Helen. Two such cavities vented to the surface close to the crater and can be seen in Figure 17. Available information indicated that the soil condition in the Shot Koa area had somewhat less strength than that at Site Yvonne and was probably more fractured than NTS soil.

This fractured condition may have accounted partly for the large crater size of Shot Koa, and some thought might be given to introducing a fracture factor, similar to the strength factor used in the Shot Cactus correlation. However, since no data exists to show the difference in crater size that could be expected from fractured soil, such a factor is not used.

The only apparent unique feature of Shot Koa was the water tank in which the device was detonated, Figure 7. It was desirable to determine if there were any data which might indicate that the water tank produced any unexpected effects. Fireball photography showed a somewhat aspherical shape as late as 2.5 msec after the detonation, corresponding to a fireball radius of 150 meters. The time to minimum, as indicated by the bhngmeters, was about 35 percent lower than would have been expected on the basis of the fireball yield determination.

Since no other unusual conditions were evident as contributing to the large crater size, it was concluded that an increased coupling of energy into the ground was brought about by the water tank surrounding the Shot Koa device. The water tank had, therefore, affected the early fireball or shock transport history of the nuclear detonation from its normal pattern of an air-ground interface shot. This may have been due to the fact that in an air-ground interface detonation there is a tremendous difference in density between air and ground. The fireball had encompassed a large area of the ground surface but had gone only a short distance into the ground by the time of hydrodynamic separation. When the device is enclosed in a water tank there is less difference in density between the water-ground interface, permitting the energy to be transported more nearly equally in all directions until the water-air interface is reached. The effects of the fireball history are more meaningful if it is realized that for a nuclear detonation at an air-ground interface less than 1 percent of the total yield contributes to the formation of the crater. A relatively small influence on the overall energy partition could have a large effect on the crater formation mechanism.

From a comparison of the above values with TM 23-200 it can be assumed that the water has acted as a tamping device to increase the coupling of energy to the soil. It would appear that

Until further data is available it can be assumed that the scaled water dimensions for Shot Koa are sufficient for maximum partitioning of energy into the ground.

Previous tests conducted with high explosives, Reference 10, show that the crater size can be increased by slightly tamping an explosive that would have otherwise vented to open air. The addition of more tamping had no effect. The cratering efficiency also increased more, percentage-wise, with a tamping or containment of a higher energy-density explosive, C-4, than a lower one, ammonium dynamite. The increase in crater radius of a tamped charge of C-4 to an un-

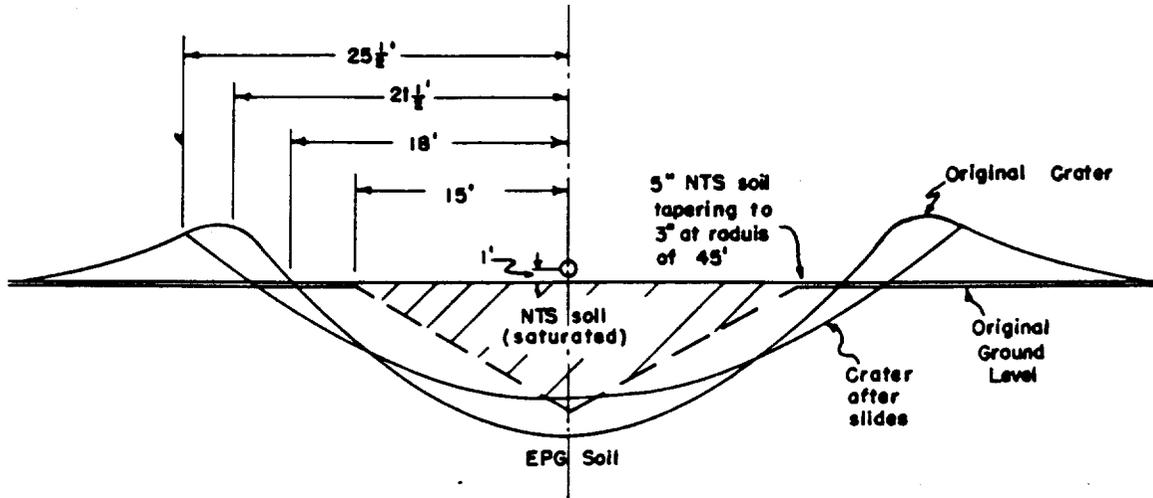


Figure 22 Shot Fig crater profile.

tamped was 15 percent, while the increase in radius of tamped to untamped ammonium dynamite was only 10 percent.

It is felt, therefore, that a containment factor of approximately 1.3 or 30 percent could be used for low-yield nuclear devices with possibly a slight increase in the factor for larger yields.

Crater Dimensions, Shot Fig. [

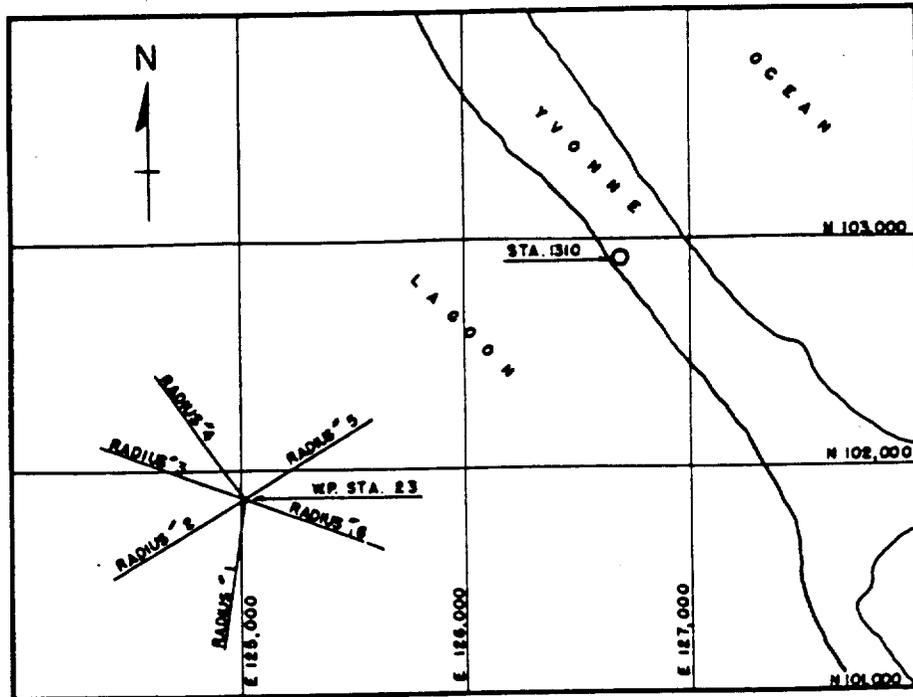


Figure 23 Shot Linden survey radii.

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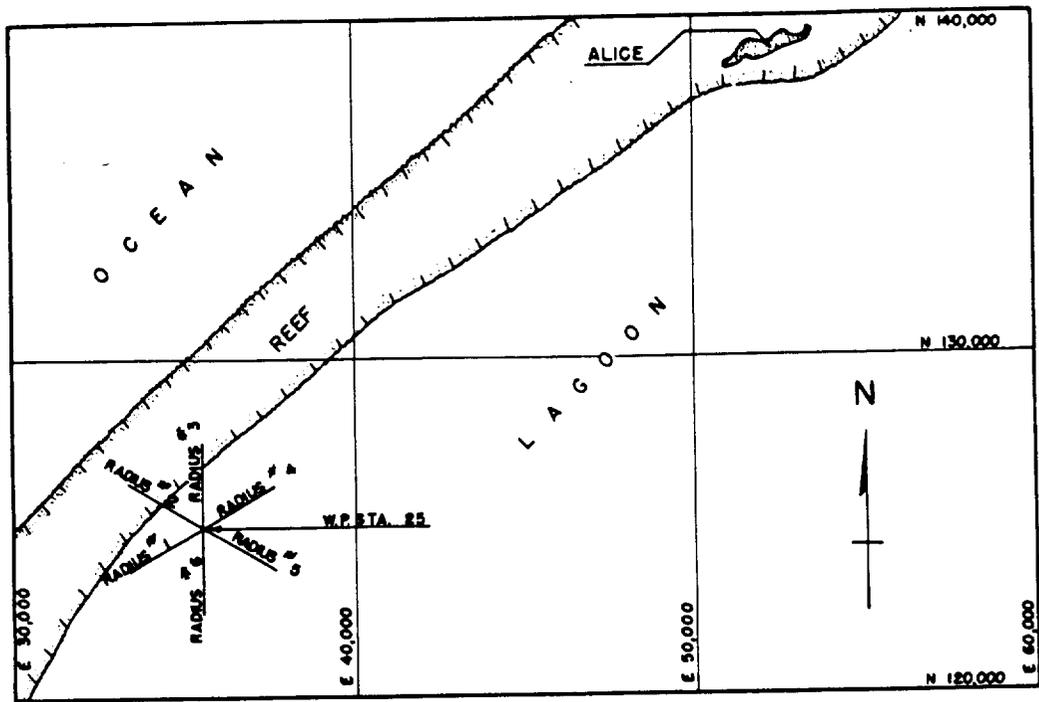


Figure 25 Shot Oak survey radii.

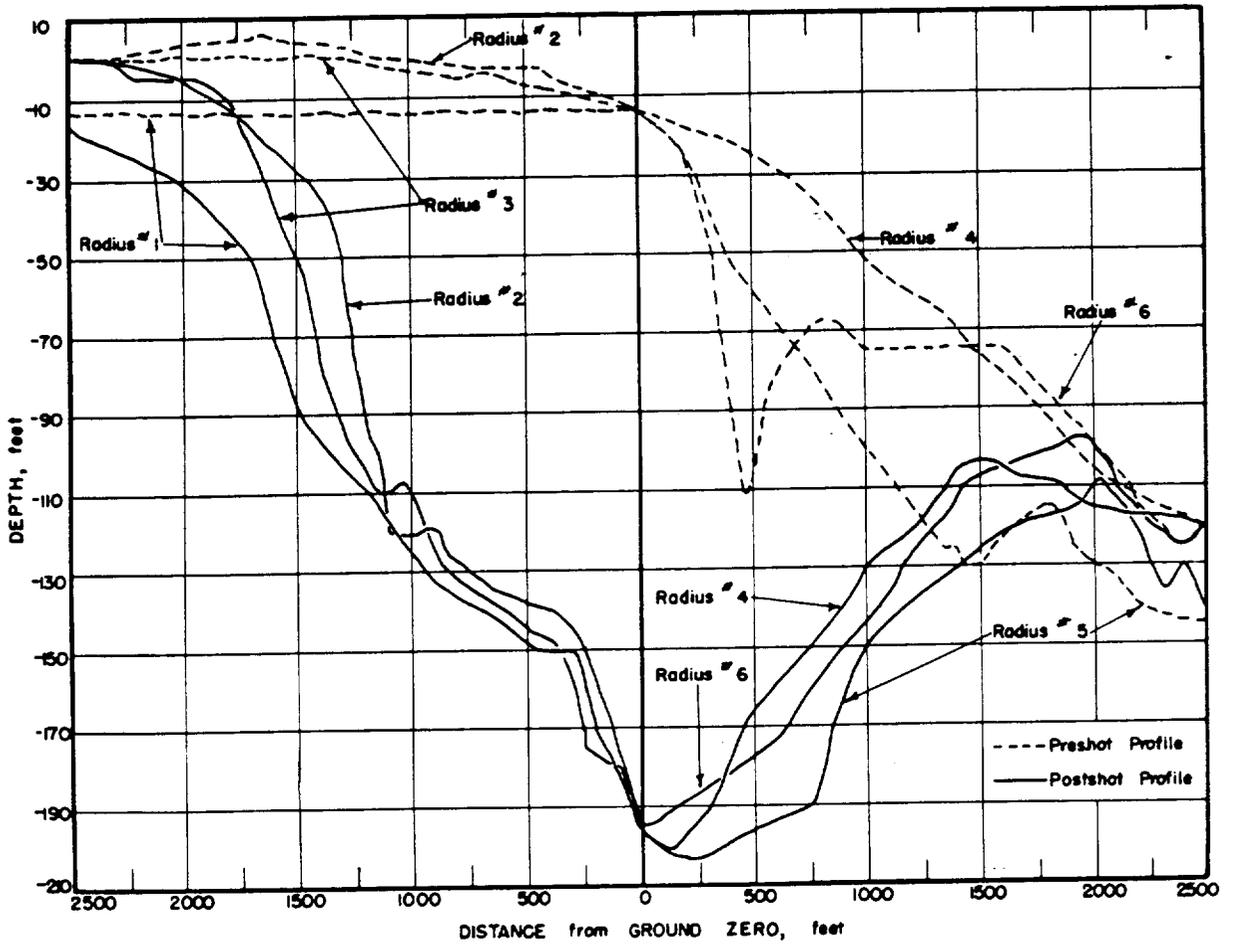


Figure 26 Shot Oak crater profile.

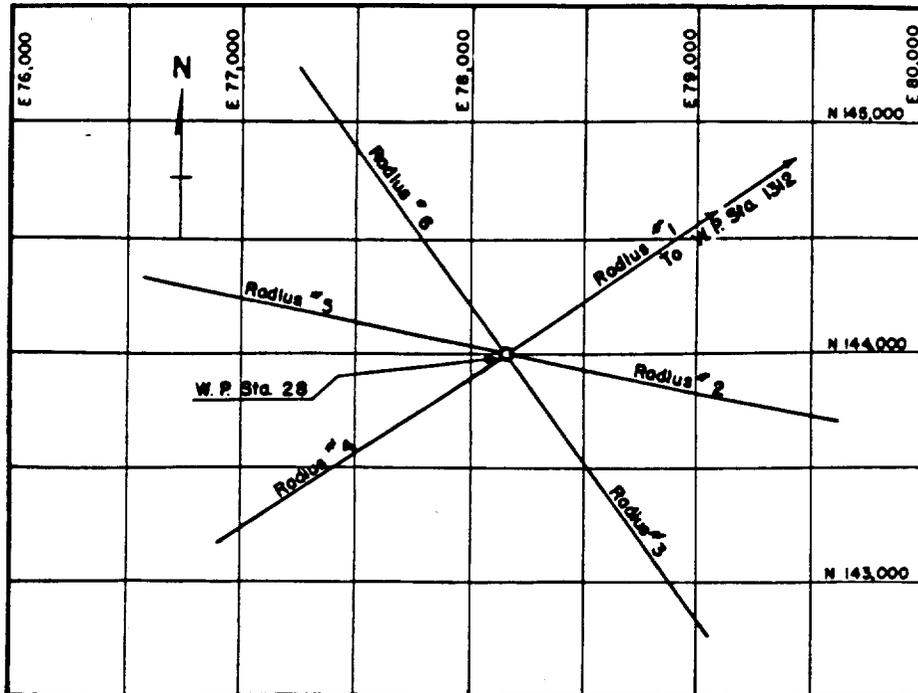


Figure 27 Shot Yellowwood survey radii.

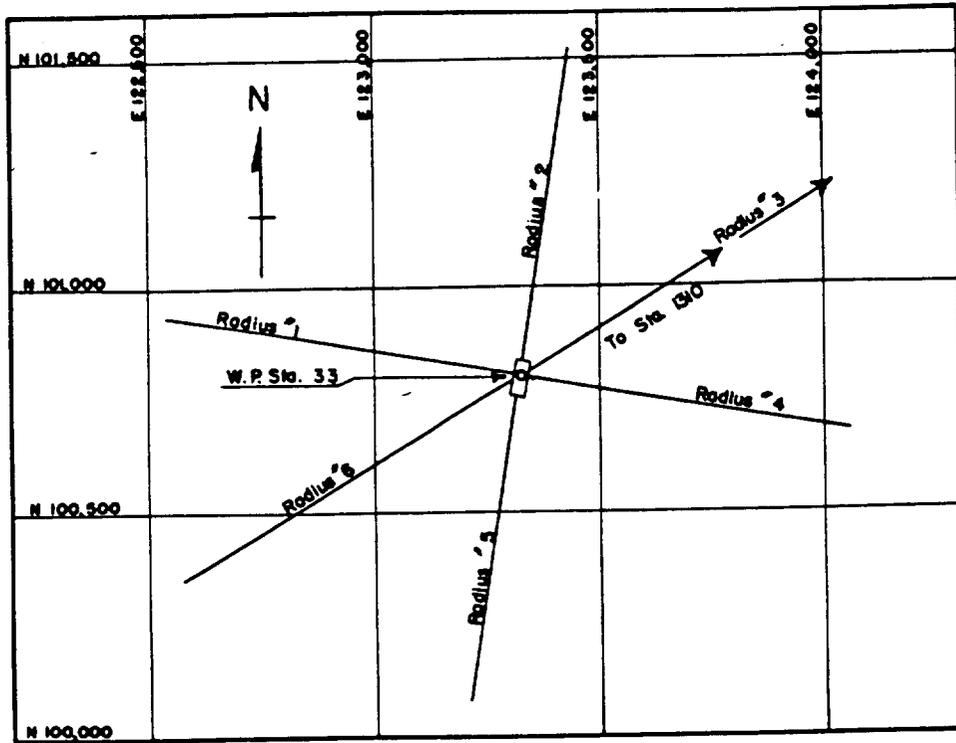


Figure 29 Shot Butternut survey radii.

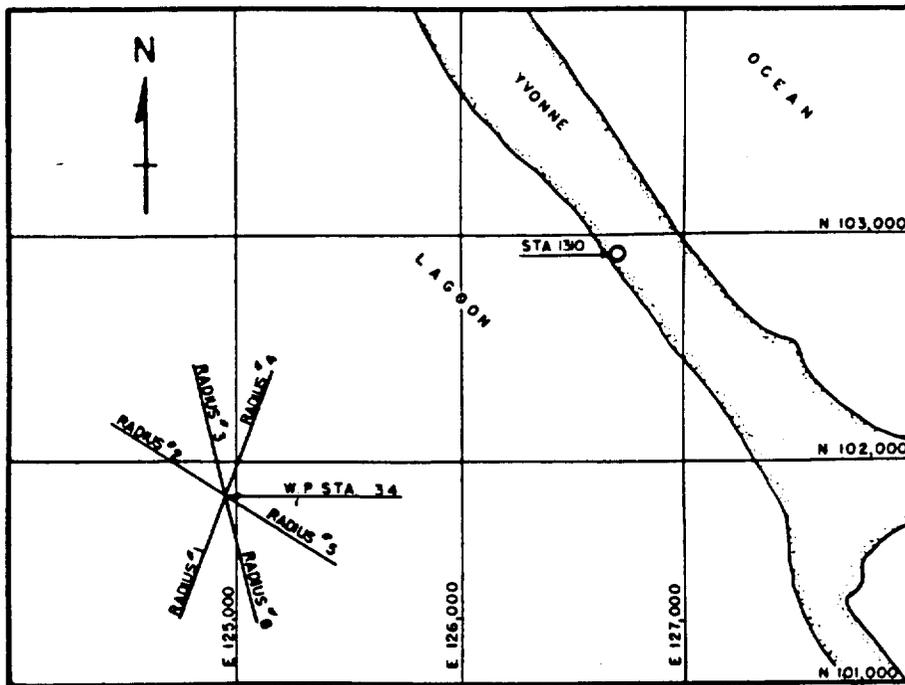


Figure 31 Shot Holly survey radii.

Crater Lip and Throwout. No consideration has been given in this report to crater lips formed from barge shots. Any lips formed by these craters have either been destroyed through washing or are not clearly defined by the fathometer data. Any conclusions, therefore, may not be valid. Of the three land shots only two, Shots Fig and Cactus, had recordable lips. Shot Koa, Figure 17, had no visible lip and it is assumed that the wave produced by the shot washed away any lip that might have been formed.

The lip of the Shot Cactus crater was irregular in height and width ranging from little or no lip on the reef or north side of the crater to peaks of 14 feet on the inland side. Lip width likewise varied from 0 to 170 feet. Large masses of saturated soil were thrown out of the crater and deposited as earth mounds for distances up to 300 feet from the crater edge. Impact craters existed as far out as 700 feet. Figures 11, 12, 35, and 36 are photographs of the Cactus area after shot time, showing the lip and mounds of throwout material. In order to give a clearer picture of the lip, preshot and postshot profiles have been constructed using the crater radii as the zero reference or datum plane, Figure 37. Representative lip height is taken to be from 8 to 14 feet and width from 115 to 170 feet. The majority of the large masses of throwout material lie within two crater radii of the crater edge.

Lack of adequate data has prevented refined methods for predicting lip dimensions. Scaling of lip height into high yield ranges, however, may not be justified. It would appear that as the yield of the device increases, the slope of the crater sides decreases and the lip height tends toward a maximum. A maximum lip height, however, should not affect lip volume. Percentage of lip volume to crater volume has been calculated from dry sand data and is probably representative of most soils, Reference 7. These percentages are 20 to 30 for near surface aboveground burst, 15 to 20 for surface burst, 10 to 20 for near surface underground burst, and 50 to 70 for deep underground burst. For a surface burst, therefore, such as the EPG shots, most of the cratered media is throwout or fallout and almost all the large masses of material or ejected fragments (throwout) are within two crater radii of the crater edge.

The EPG shots neither supported nor invalidated the prediction method for lips given in TM 23-200 since the limits of accuracy given in the TM were large enough to allow a wide variation in the lip dimensions. The Shot Cactus lip, for example, could range between 3½ to 13½ feet high and 127 to 213 feet wide.

Depression Measurements. Permanent vertical depression of the ground surface was measured at NTS from an air burst and it was felt desirable that these measurements be repeated for a surface burst at the EPG. These measurements were made using concrete gage pads as stations for both Shots Cactus and Koa. Transient displacement measurements made by Project 1.8 could then be used as a check. The data was not expected to have a high degree of accuracy because of the probability of postshot ground motion produced by relief of internal stress and wave action caused by other shots.

Postshot surveys were not completed until 1959 because of the hazard to survey personnel from the high residual radiation levels. When recovery of stations was attempted by Holmes and Narver, it was found that most of the stations had been destroyed through the use of bulldozers and draglines by project personnel effecting a fast recovery of their instruments with minimum radiation exposure.

Depression measurements for both Shots Cactus and Koa are listed in Table 10. There are only two measurements of value for Shot Cactus, Stations 171.05 and 181.03. Station 181.03 was at a distance of 850 feet from ground zero and gave a downward displacement of 0.72 inch. The overpressure was approximately

Transient displacement measurements made by Project 1.8 at approximately this distance, however, indicated a maximum downward movement from the rest position of 0.89 inch with a minimum movement above rest position of 0.82 inch and a residual displacement of 0.22 inch above the position of rest. Station 171.05 was 980 feet from ground zero and gave a permanent downward displacement of 1.08 inches. The overpressure at this station was approximately

Since only one transient displacement measurement was obtained for Shot Cactus a comparison at this station was not possible.

The only records of value for Shot Koa were for Stations 180.02 and 180.03, which were at distances of 3,131 and 3,950 feet from ground zero. Station 180.02 showed a permanent displacement of 4.57 inches downward while Station 180.03 registered an upward displacement of 4.24 inches, giving an increased elevation. An overpressure of approximately

was registered close to Station 180.02 and an approximately



Figure 35 Shot Cactus crater lip.



Figure 36 Shot Cactus crater lip.

was measured close to Station 180.03. Comparable transient measurements were made by Project 1.8 at distances of 3,144 and 3,950 feet from ground zero. The gage records at 3,144 feet registered a maximum downward displacement of 2.66 inches with a residual of 1.16 inches. An early downward movement of 1.94 inches was registered at 3,950 feet with a residual displacement of 2.70 inches.

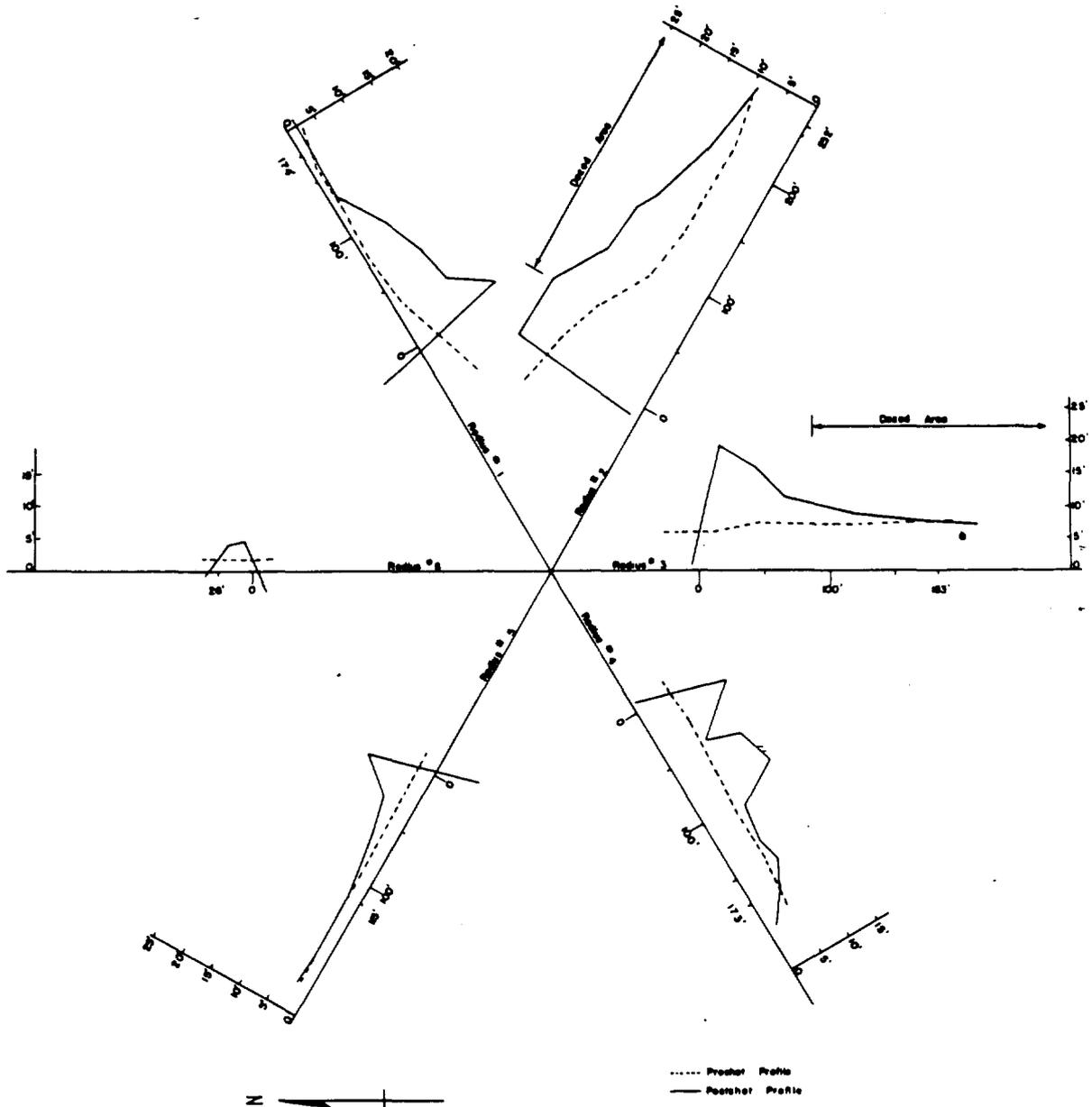


Figure 37 Shot Cactus lip profile.

Additional measurements were made on the cement blocks supporting Pipeline 1131. This data is also presented in Table 10. These measurements, however, are considered of little value since the blocks were supported by X frames anchored into coral or cemented sand at depths from 20 to 30 feet, and it is suspected that some movement of the blocks was due to the pipeline being ripped from its mounts.

No evaluation or conclusions are possible from the permanent depression measurements. There seems to be no correlation with transient displacement measurements where comparison

is possible. The possibility of the stations being altered during gage recovery, outside effects from other shots, and the gradual change of stations with time cast a reasonable doubt on the validity of the data available.

## CONCLUSIONS

It is concluded that:

1. A suitable factoring system can be developed for adjusting raw crater data to a standard condition. Additional data, of different media response to shocked conditions, is needed in order to develop these factors. This can probably be done by a system of high-explosive tests under controlled conditions so that parameters such as soil strength, void ratio, moisture content, and density can be varied and their effects on crater size evaluated.
2. Results of Operation Hardtack plus previous results of Operation Redwing have conclusively indicated that the detonation of devices inside relatively small water tanks appreciably increases the crater dimensions by acting as tamping material.
3. The cratering curves given in TM 23-200 for water surface burst are not in agreement with craters measured from Operation Hardtack barge shots. Craters formed under these conditions were larger than previously expected.

## RECOMMENDATIONS

It is recommended that:

1. A more refined factoring system for adjusting crater dimensions be developed so that shot data can be reduced to a standard condition.
2. Future detonations of nuclear devices having unusual environmental conditions be closely monitored for associated effects on craters.

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