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Scientific Director's Report of Atomic Weapon Tests at Eniwetok, 1951
Annex 1.6 Blast Measurements
Part VI—Ground Shock Measurement
Section 2—Crater Survey

F. B. Porzel
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

December 1953

NOTICE:
This is an extracted version of WT-109 OPERATION GREENHOUSE, Annex 1.6, Part VI, Section 2.

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The purpose of this report was to study the general characteristics of the craters formed from nuclear explosions in connection with Operation Greenhouse to formulate general rules as to their size and shape.

On the basis of the results, it was concluded that (1) craters on Eniwetok Atoll may be roughly described as conical sections and scaling relationships for the depth, radius, and volume are given as functions of yield; (2) crater formations are significantly affected not only by local soils but probably by the major geological structure of the Atoll; and (3) the completely different phenomenology involved in nuclear explosions in comparison with TNT denies any justification for attempting to scale to correlate the results of TNT with nuclear explosions short of the detailed considerations of the very different early hydro-dynamic history of each explosion.

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FOREWORD

Classified material has been removed in order to make the information available on an unclassified, open publication basis, to any interested parties. The effort to declassify this report has been accomplished specifically to support the Department of Defense Nuclear Test Personnel Review (NTPR) Program. The objective is to facilitate studies of the low levels of radiation received by some individuals during the atmospheric nuclear test program by making as much information as possible available to all interested parties.

The material which has been deleted is either currently classified as Restricted Data or Formerly Restricted Data under the provisions of the Atomic Energy Act of 1954 (as amended), or is National Security Information, or has been determined to be critical military information which could reveal system or equipment vulnerabilities and is, therefore, not appropriate for open publication.

The Defense Nuclear Agency (DNA) believes that though all classified material has been deleted, the report accurately portrays the contents of the original. DNA also believes that the deleted material is of little or no significance to studies into the amounts, or types, of radiation received by any individuals during the atmospheric nuclear test program.

Scientific Director's Report of Atomic Weapon Tests at Eniwetok, 1951

Annex 1.6

Blast Measurements

Part VI Ground-shock Measurements

Section 2

6

BLAST MEASUREMENTS

Part VI—Ground-shock Measurements

Section 2

Crater Survey

by

FRANCIS B. PORZEL

Approved by: FREDERICK REINES
Director, Program 1

Approved by: ALVIN C. GRAVES
Scientific Director

Los Alamos Scientific Laboratory
Los Alamos, New Mexico

December 1953

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Chapter 1

Introduction

1.1 PURPOSE

The purpose of this test was to study the general characteristics of the craters formed from nuclear explosions in connection with Operation Greenhouse at Eniwetok and, if possible, to formulate general rules as to their size and shape.

The crater shape, especially at Eniwetok, may well be a dynamic rather than a static problem, as will become apparent in the discussion of results. In general, this report is restricted to the description and study of the craters at a late stage when they were in relatively stable configuration. Data are not available on, nor does the report consider in detail, the intermediate configurations of the craters.

1.2 HISTORICAL

This test was performed at the instigation and request of Frederick Reines, Director of Program 1 for Operation Greenhouse. In his directive, reproduced in Appendix A, detailed plans were given for the array of stakes, as well as for surveys to be made before and after Dog and Easy shots.

Edward J. Zadina, then of J-Division, Los Alamos Scientific Laboratory (LASL), was in charge of the project until he left J-Division in the spring of 1952, at which time the responsibility for the report was assigned to the present author.

Data for the crater survey were received in the late summer and fall of 1952. The preparation of the report has been delayed, however, in part by preoccupation with other operations. In the meantime, the crater survey for Mike shot of Operation Ivy became available and has been incorporated as part of this report. The author would have liked to make more detailed analyses and study of the results, which the subject deserves. However, some worth-while conclusions appear justified from a cursory study; this, together with his impending transfer from LASL, makes it worth while to publish the report in its present form.

1.3 BASIC THEORY

1.3.1 General Characteristics of a Nuclear Explosion at a Soil-Air Interface

Some general characteristics of the phenomena involved in a nuclear explosion at an interface between soil and air is contained in Report LA-1529.[1] This was based in turn on a detailed study for the nuclear explosion in soil in preparation for Jangle Underground shot.

A principal result of both these studies is the vastly greater material and shock velocities in air relative to those in soil during the extremely high pressure phases of a nuclear explosion. This results in a very small energy transfer to the soil, and in relatively broad and shallow craters. In LA-1529 methods are suggested and carried out for calculating the peak pressure as a function of distance beneath Ground Zero. The craters from nuclear explosions are expected to be markedly different in size and shape from those of TNT, and no attempt is made here to scale craters between TNT and nuclear explosions. Figure 1.1 is reproduced from LA-1529 and shows the relative shape of the shock configuration for both nuclear explosions and TNT. Although the figures are intended to be qualitative, they are not exaggerated; the pronounced difference in shape of the ground shock is occasioned by the very different relative velocities between soil and air at the very high pressures associated with the beginning of nuclear explosions, in comparison with corresponding relative velocities at the lower pressures associated with the beginning of TNT explosions.

gard to the equation of state, the material velocity, u, is given by

$$u^2 = (P - P_0)(V_0 - V)$$

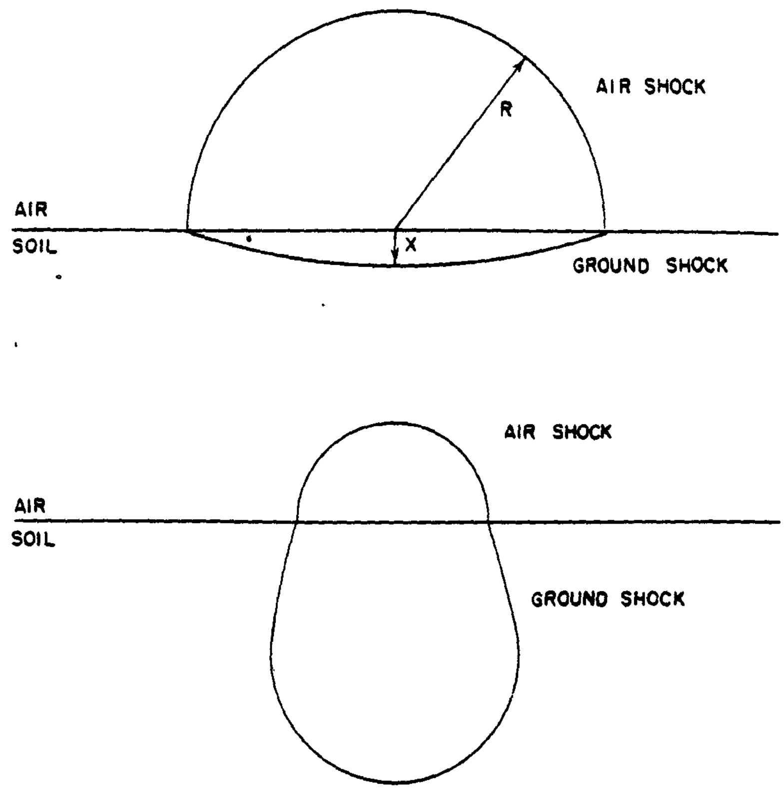

Fig. 1.1 Schematic Comparison of Nuclear Explosion and Small-charge Explosion. Note the broad shallow character of the nuclear shock in soil, as shown above, with the relatively deep shock from TNT, shown below.

The small energy transfer on nuclear explosions follows from the high density and incompressibility of soil relative to air at comparable pressures. The time rate of work per unit area of shock front in any substance is proportional to the product

$$\dot{W} = Pu$$

where $\dot{W}$ = the rate of work per unit area and time
P = the absolute pressure behind the shock
u = material velocity

Using only conservation of mass and momentum in the Rankine-Hugoniot equations, without regard to the equation of state, the material velocity, u, is given by

where P = absolute pressure behind the shock
P_0 = ambient pressure ahead of the shock
V = specific volume behind the shock
V_0 = ambient specific volume ahead of the shock

It follows then that the rates of doing work by the shock in soil and the shock in air are related by

$$\frac{\dot{W}_{soil}}{\dot{W}_{air}} = \sqrt{\frac{\left(1 - \frac{V}{V_0}\right)_{soil}}{\left(1 - \frac{V}{V_0}\right)_{air}} \frac{\rho_{air}}{\rho_{soil}}}$$

at the same pressure level in both media. The incompressibility of soil means that the quantity $1-(V/V_0)$ is not far different from zero, whereas for strong shocks in air the same quantity is not far different from 1. The density of air relative to soil is in the order of 10^{-3}. At Eniwetok, the water table comes within a few feet of the surface, the interstices of soil are water-filled, and the incompressibility of water further favors the propagation of shocks in air over the shock in ground.

The greater area of the air shock is indicated in Fig. 1.1, which follows from similar considerations involving the shock velocity, and this area enhances the transfer of energy to the air by another factor of approximately 2. In LA-1529 it was shown that, over a substantial range of pressures, the relative rate of work of the ground shock to the air shock was around 0.001; something less than 0.1 per cent of the energy of the bomb is transferred to the soil and hence available for crater formation. The situation is somewhat different in very porous soils, such as at Nevada Test Site. There the soil may contain 40 per cent air by volume, so the quantity $1-(V/V_0)$ is not small, but a number more like 6/10. In this case, the relative rate of work in soil to air is still proportional to the square root of the density ratios and is more like a factor of only 100 to 1 in favor of air over soil. In the paper on nuclear explosions in soil, it was predicted that slightly less than 1 per cent of the energy could be transferred to the soil and hence available for crater formation at Nevada Test Site.

Of course, crater formation is not likely to be a uniform or reproducible process in any real soil because of marked inhomogeneity in compressibility as well as in density, which is due in turn to pockets of air or water, rock formations, or differences in particle sizes. At the outset, the most one can hope for is a general description which suits the average condition. Local variations in crater size by factors of 2 seem entirely reasonable.

1.3.2 Geologic Structure of the Atoll at Eniwetok

Crater formation at Eniwetok is further beset by difficulties involving the geologic structure of the Atoll itself, which was shown by geologic investigations under the direction of H. K. Stephenson of LASL and Roger Revelle of the Scripps Institution of Oceanography.

The Atoll rests on a consolidated basalt floor which is about 4000 ft below sea level. The overlying 4000 ft are mostly loose, unconsolidated sands or coral but interspersed with large pockets of water and presumably local stringers or networks of coral formation. The relatively loose material is contained on the ocean side by a sheath of coral rock of varying thickness which is expected to have numerous weak spots because of joints and fissures characteristic of coral formations. The excess density of this inner material over that of water represents enormous potential energy by virtue of its elevation above the ocean floor. The Atoll is considered to be in a metastable state but is presently contained by the structural strength of the coral rock, by rock formations within the sands, and by internal friction in the sand formation.

The theory of dilation has been applied to this geologic structure. The passage of the ground shock may break up the coral sheath and rock formation to an unknown extent and disturb the matrix of sand particles. The theory suggests that the sand formation will momentarily behave as a dense liquid after passage of the shock and flow plastically; the excess hydrostatic pressure may now breach the weakened sheath, permitting the sand material to flow to lower depths. If this structural failure occurred at a sufficient depth, the potential energy released could become comparable to the energy in the destructive oceanwide tsunami, and, by virtue of this trigger mechanism, this energy would greatly exceed the small amount of energy transferred to the soil from the nuclear explosion.

The purpose of LA-1529 was in good part to show that a large-scale geologic failure of the Atoll could not be reasonably expected. On the other hand, the theory and the geologic structure suggest the possibility that holes or pockets may occur in or near the crater, which would be more representative of the geologic structure than of the nuclear explosion. Near a structural weakness material could flow through fissures in the ruptured wall, both because of the shock pressures and because of gravity.

1.3.3 Hydrodynamic Variables at the Ground for a Tower Shot

Some estimates of the magnitude of the hydrodynamic variables in the air shock with their distribution in space are contained in a study by the author and are reported in the Greenhouse Handbook of Nuclear Explosions.[2] This provides rough theoretical estimates for the air pressures near Ground Zero of Greenhouse Easy

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shot. No experimental data are available in the region of the calculation, but ball and crusher gauge measurements by the Naval Ordnance Laboratory at a ground point just beyond the region of these calculations appear to be in reasonable agreement with them. Very crude agreement with the theory was also afforded by the structural failure of the snap samplers on Greenhouse. These samplers had been designed according to the specifications in the theoretical study and, on Greenhouse Easy shot, successfully withstood the blast, whereas on Greenhouse George shot, where the reflected pressures were some ten times greater, the snap samplers were partially demolished.

The values of pressure, density, and material velocity and their time variation in the region of regular reflection beneath the tower were calculated for a 50-kt bomb detonated on a 300-ft tower. Using a theory of strong shocks with variable gamma, all pertinent hydrodynamic variables in the incident wave at the ground were calculated from Operation Sandstone fireball measurements. The necessary equations of state were based on several sources and correlated by material later given in Thermodynamic Properties of Air.[3] The corresponding peak values in the reflected wave were then calculated, using a treatment of regular reflection theory, which was reformulated to permit treatment of variable gamma. The calculated peak values for reflected pressure, density, and material velocity at the shock front furnished the boundary conditions at the front of the reflected wave for regions close to the ground. From these conditions, the mass flow behind the reflected shock was derived; the procedure is similar to the simpler problem of the free-air wave as in IBM Problem M, but using more rapid graphical and computational techniques. Pressure, density, and material velocity were necessarily carried forward during the integration, and temperatures were also deduced using the equation of state for high pressures in Thermodynamic Properties of Air.[3]

Figures 1.2 to 1.5 are reproductions of Figs. 4.7 to 4.10 in WT-103, Greenhouse Handbook of Nuclear Explosions, and give the results of this calculation, as the time variation of pressure, density, material velocity, and temperatures, respectively, for various distances from Ground Zero. The curves for peak values are also shown. The early wave form is somewhat different from that of a free-air burst, presumably because of the reflection process and the large entropy changes involved. These curves were prepared and should be regarded primarily as an exercise in strong shock hydrodynamics but probably constitute a reasonable estimate for 50 kt on a 300-ft tower. In general, the results cannot be scaled to different tonnages or different tower heights, except for rough orders of magnitude.

Intuitively, one might expect the pressure-distance curve to be considerably flatter at angles within 45° of the bomb because the slant distance does not change greatly and because, at low pressures, the pressure multiplication does not vary greatly as a function of angle. This is not so in strong shocks for two reasons: First, the pressure multiplication falls off quite rapidly with increasing angle of incidence. This effect is then aggravated for the tower height and yield of Greenhouse Easy shot by the influence of variable gamma; as an example, $\gamma = 1.4$ gives a pressure multiplication of 8 at normal incidence, whereas for $\gamma \cong 1.2$ the pressure multiplication is near 12 or 13 at normal incidence.

Figures 1.3 and 1.4 contain the time variation of density and material velocity, respectively, and these are shown because they are the parameters involved in the dynamic pressure. The density falls off in a manner similar to the manner in which peak pressure falls off with distance. The material velocity, of course, is zero at Ground Zero, increasing rapidly to a maximum value at the end of regular reflection. As a consequence, the dynamic pressure, $\frac{1}{2}\rho u^2$, would follow a curve somewhat similar to the velocity vs distance curve, but this is not of primary importance because the flow is parallel to the ground. As such, the material velocity might contribute strongly to a scouring action by removing loose material near the edge of the crater, and, if anything, would tend to flatten the early crater rather than contribute to depth at the center.

Figure 1.5 gives the temperatures on the ground vs time and is of some further interest because the peak shock temperatures fall in the range 5000 to 9000°K. This is a range of temperatures which is favorable to the production of NO_2 and probably means that soil vaporization due to radiative transport is much less serious than one might suppose at first as a contributing mechanism for crater formation. The relative coolness of this layer and, in fact, the particular temperature range in which it falls, suggest that, if for no other reason, the ground surface will be protected from the radia-

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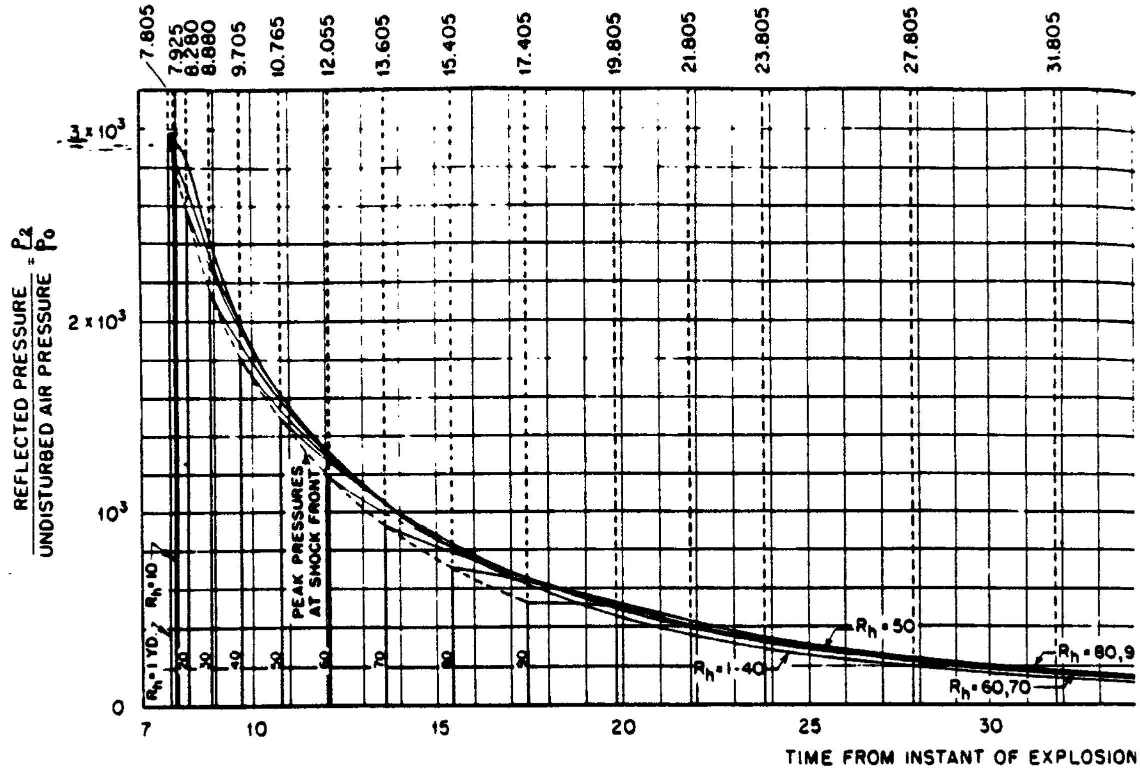


Fig. 1.2 Reflected Pressure on the Ground vs Time for 50 Kt, 300-ft Height ot B

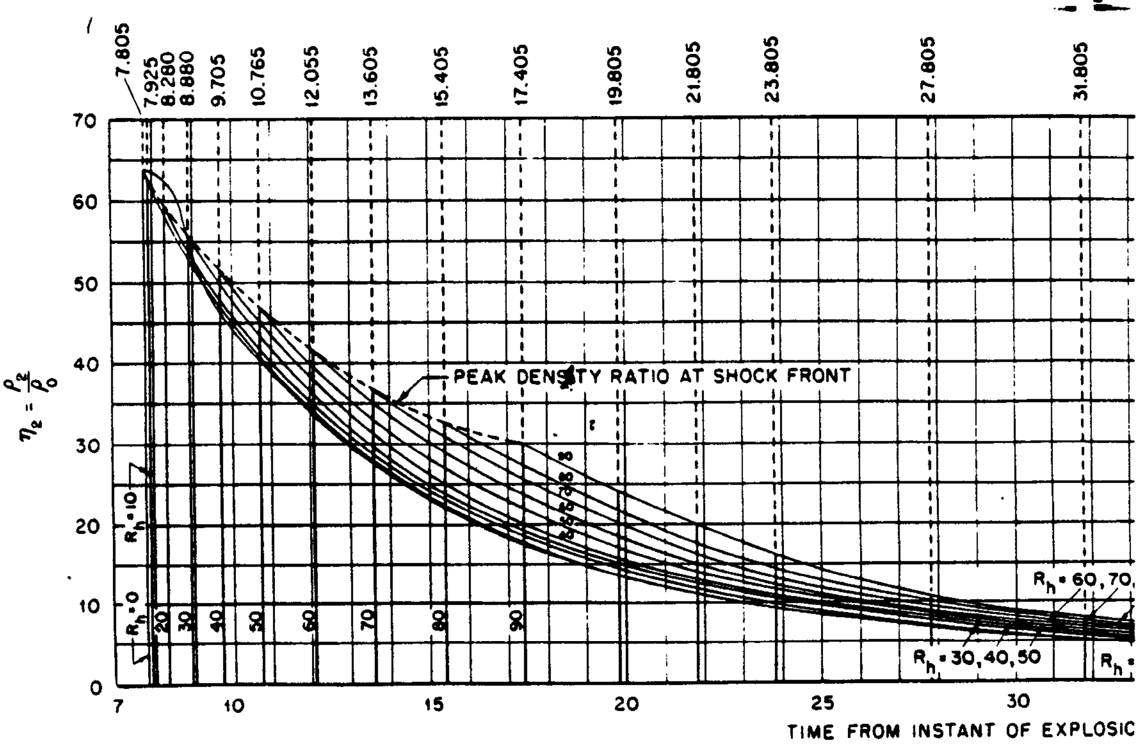
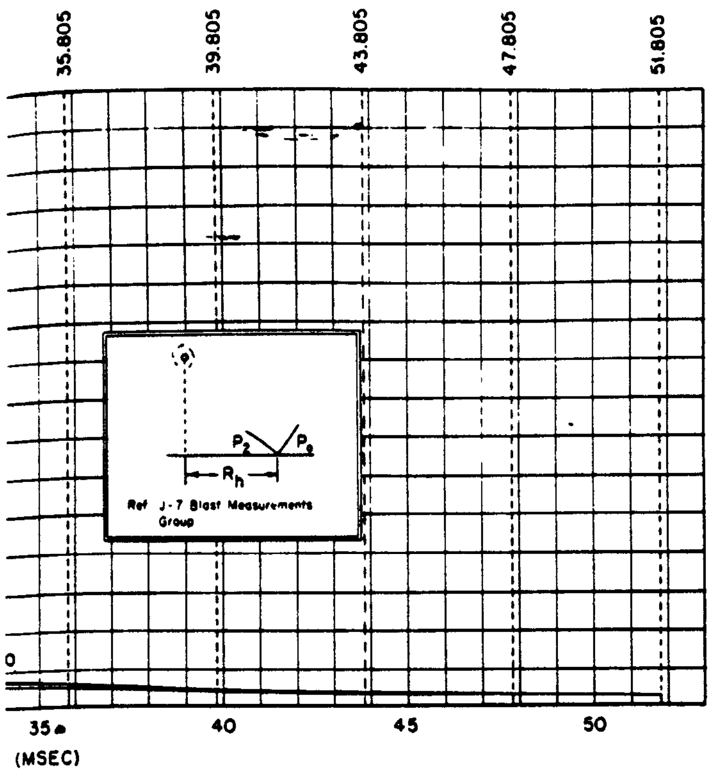
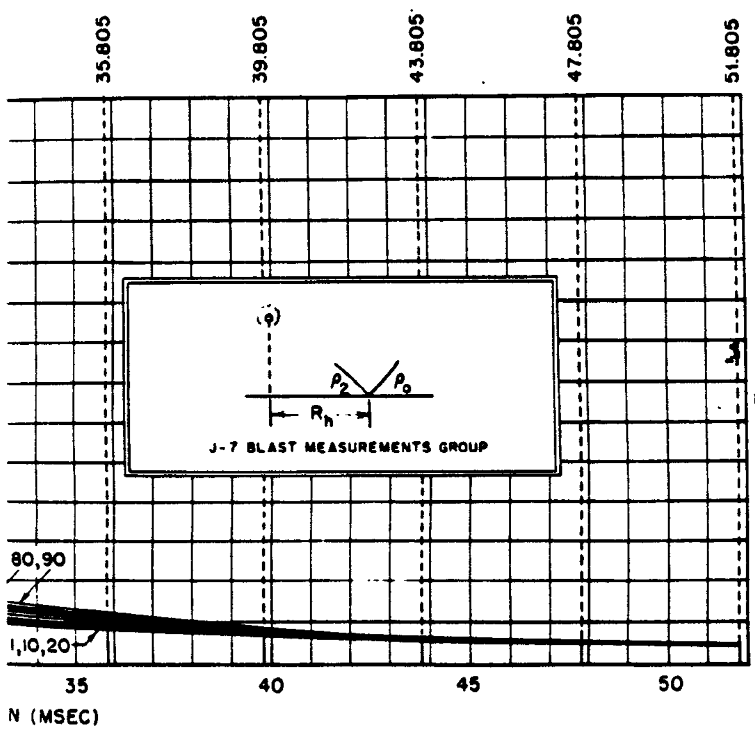


Fig. 1.3 Ratio of Air Density in Reflected Region on the Ground to Density
Height of Burst, at Several Horizontal Dist



ırst, at Several Horizontal Distances R_h



ɔf Undisturbed Air vs Time for 50 Kt, 300-ft
ances R_h

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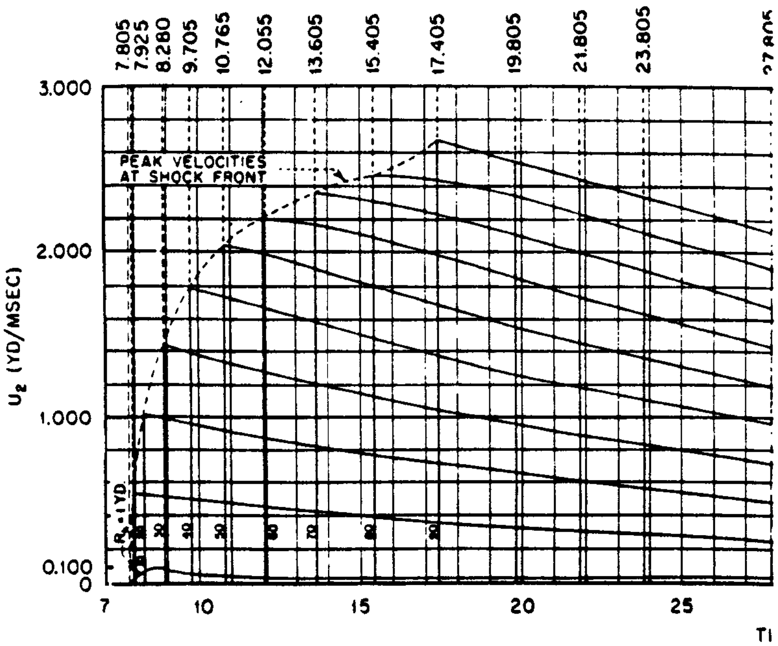

Fig. 1.4 Material Velocity U_2 in Reflectec

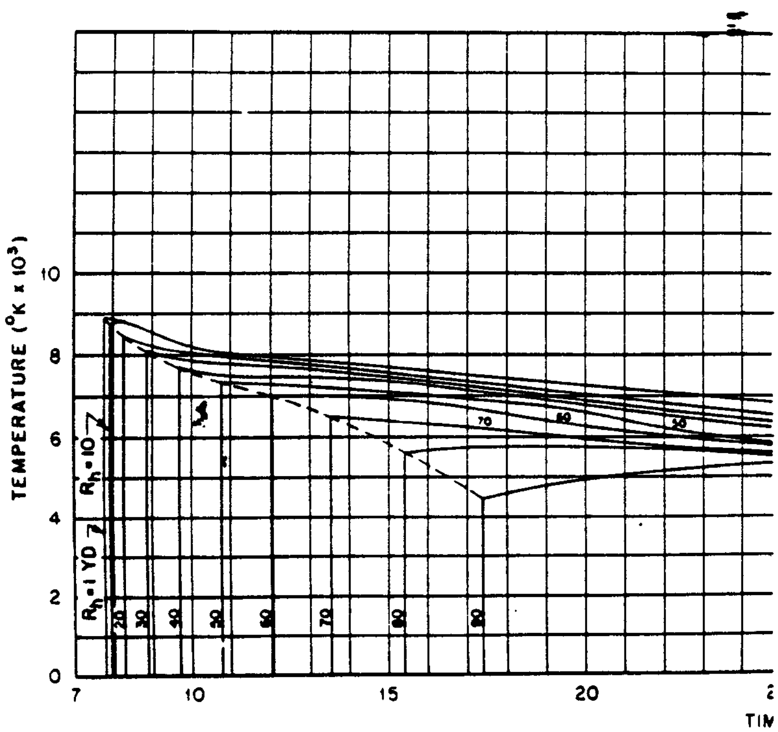

Fig. 1.5 Temperature on the Ground vs T

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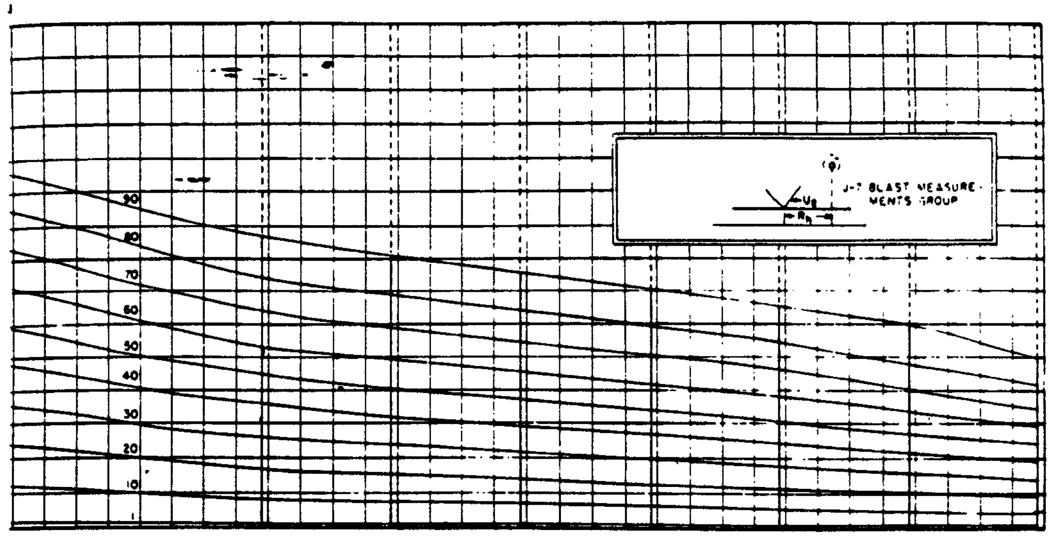
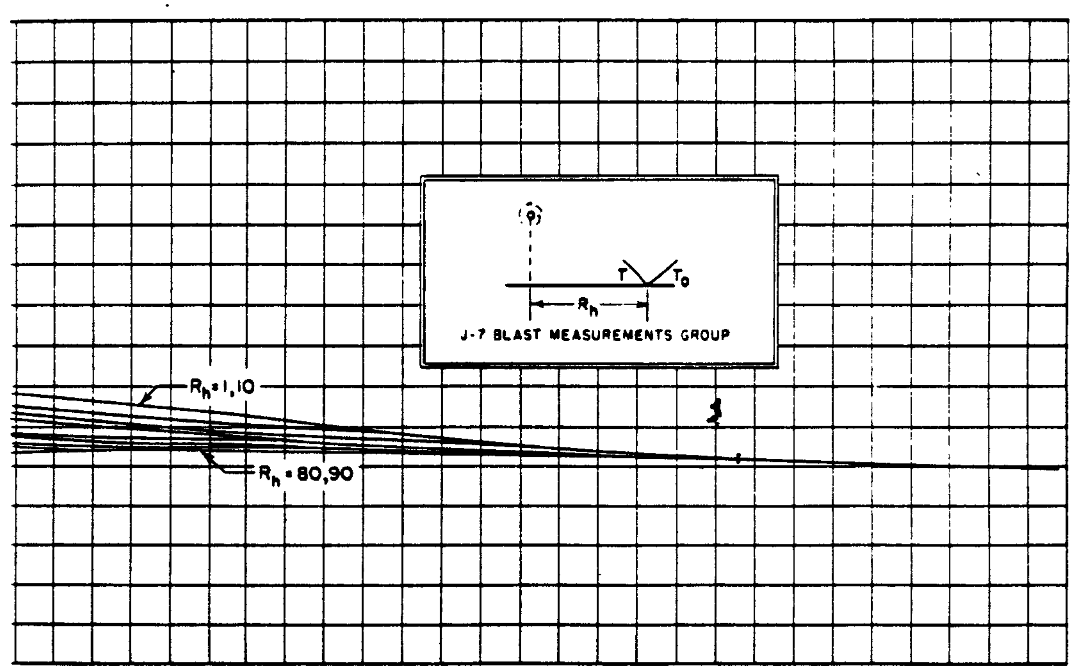


! Region on the Ground vs Time for 50 Kt, 300-ft Height of Burst, at Several Horizontal Distances R_h



ime for 50 Kt, 300-ft Height of Burst, at Several Horizontal Distances R_h

tion on the interior of the fireball by a layer of NO_2 near the surface. Even apart from these arguments, the opacity of soil is high, so that the temperature must fall off extremely rapidly into the soil. The heat capacity of the soil itself provides a blanketing layer which is cool enough to shield the surface from high-frequency radiation on the interior of the bomb. From these considerations we do not believe that soil vaporization is a material factor to crater formation for nuclear explosions over soil.

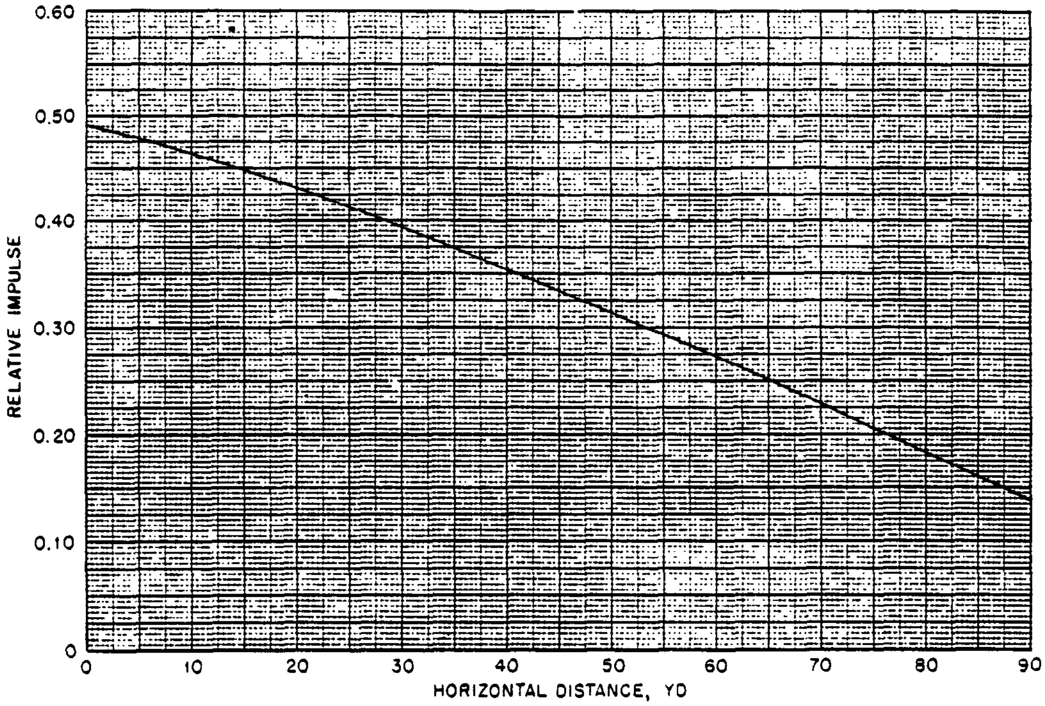


Fig. 1.6 Relative Impulse vs Horizontal Distance. Theoretical calculation derived from Fig. 1.2. Note approximate linear delay of impulse with distance, which would probably become negligible near 200 yd.

Figure 1.2 is used to measure the relative impulse as a function of horizontal distance, and these results are plotted in Fig. 1.6. A striking result of this graph is the linear decay of relative impulse as a function of horizontal distance. Note that the impulse would be relatively small if extrapolated to distances like 600 ft.

1.3.4 Scaling of Craters for Nuclear Explosions

Despite the inherent fluctuations in soil constants, it appears possible to draw some general conclusions regarding the shape of craters for nuclear explosions from the preceding discussion.

A starting point for the discussion of scaling might be similarity scaling, but, without the risk of assuming it, crude similarity was obtained as a derived result in Fig. 8 of LA-1529 for the theoretical comparison of Greenhouse George shot and the Operation Ivy Mike shot. By similarity, it is meant here that the same pressure would occur at a depth in soil on Mike which is roughly related as the cube root of the yield ratio to the corresponding depth on George. The difference between a surface shot and a tower shot is less than might be expected at first because the shock velocities in air are so much greater than the shock velocities in soil; the shock from a surface burst will have traveled only a few feet in soil by the same time the incident shock in air would have reached the ground from a tower shot. On the relatively long time scale involved in the propagation of shocks in soil, both a surface shot and a tower shot can probably be considered surface shots so far as the ground is concerned.

From this point of view, one might simply expect that both the depth and width of the crater should scale like $W^{1/3}$; thus the volume of the crater would be proportional to the energy transferred to the ground. In the absence of detailed studies involving many yields at many different pressure ratios and soil characteristics, the results of Fig. 8 of LA-1529 are some assurance, if meager, that in a homogeneous soil similarity scaling might be expected to hold.

We might reasonably expect the crater radius to scale like $W^{1/3}$ for the following reasons. The soil displacement probably involves some sort of threshold below which no deformation takes place. If, as in the case of strong shocks, the ground shock is principally controlled by the air shock, then the same value of pressure occurs at distances like $W^{1/3}$.

The crater depth presents a different aspect. At these high pressures it is believed possible for the soil to move in plastic flow, which probably implies that the movement of the soil is not simply a function of the peak pressure but is probably a strong function of the pressure duration as well. The Atoll structure suggests that such flow is possible at Eniwetok, and one could therefore expect relatively deeper craters than those which would be indicated by similarity scaling alone. Near Ground Zero then, even though the depth to which a given pressure will occur scales as $W^{1/3}$, this pressure exists for a time which is $W^{1/3}$ times longer on the larger bomb. This suggests that the depth of the crater near Ground Zero might behave more readily like $W^{2/3}$ rather than $W^{1/3}$. On tower shots there is some jetting down the tower legs, which constitutes a preferential transmission of energy in the region immediately surrounding the tower, and suggests a somewhat deeper crater near Ground Zero. At the same time, the crater represents a compromise between other competing mechanisms. There is a general flatness to the crater occasioned by the relative propagation velocities for the shock in air and soil from which one would expect the crater profile to be concave upward, as in Fig. 1.1. On the other hand, the presence of fissuring in the Atoll structure suggests that the shape of the crater could be concave downward near the center if a sink hole develops. Superimposed on these competitive mechanisms is the final downward movement of material in the crater toward the center, as in reaching a stable angle of repose. This leads to the expectation that at Eniwetok the model of the crater as a conical section (straight-line profile) is probably as reasonable as any for a general description.

From the foregoing considerations, we assume that the crater is a conical section of radius proportional to $W^{1/3}$ and depth proportional to $W^{2/3}$; thus the volume is

$$V = \frac{1}{3}\pi R^2 d W^{4/3}$$

where R is the radius of the crater and d is the maximum depth at Ground Zero. We also recognize this as a crude description at best.

REFERENCES

1. F. B. Porzel, Soil Pressures and Energy Transfer on Mike Shot, Los Alamos Scientific Laboratory Report LA-1529, October 1952.
2. B. Suydam et al., Greenhouse Handbook of Nuclear Explosions, Greenhouse Report, Vol. III, WT-103, p. 29, March 1951.
3. F. B. Porzel, Thermodynamic Properties of Air, J-Division, Los Alamos Scientific Laboratory, September 1951.

Chapter 2

Procedures and Test Results

2.1 PROCEDURES

Test procedures for Dog and Easy shots of Operation Greenhouse were carried out as directed in Appendix A. An array of stakes was located and surveyed before and after each shot by Holmes and Narver (H&N). The description of the method, together with the detailed results, are contained in Appendix B for these two shots.

On George shot no formal data were taken, but some estimate of the crater was obtained from a topographic survey made of Eberiru more than a year after the shot. No precise vertical control is available from this comparison, but it appears reliable that the original island had been leveled flat at an elevation about 10 ± 1 ft above mean sea level. The present ground configuration does not represent the crater accurately because sea water soon filled the George crater through a breach on the lagoon side, and this water flowed in and out of "Lake George" with the normal rise and fall of the tide; both erosion and deposition occurred. Subsequently, parts of the area were bulldozed to isolate the highly radioactive lake in the crater from the lagoon.

The survey for Mike was accomplished by H&N, using standard survey procedures and soundings; this was done about 2 weeks after shot day.

2.2 RESULTS

The results for Dog and Easy shots are presented as contour maps in Figs. 2.1 and 2.2, respectively. Owing to a scarcity of points, the contour lines are not accurate in detail, but merely indicate the general shape of the crater. The Easy crater is relatively uniform. The Dog crater is bowl-shaped and contains several mounds. The contour maps were prepared from the data in Appendix B by subtracting the final elevation from the initial elevation at each stake; hence the contour maps represent the change in depth rather than the craters as they presently exist.

Figure 2.3 is the contour map of the present George crater as prepared by H&N. Assuming that the original island was flat and 10 ft above high tide and that no shifting occurred, the contour map is a representation of the change in depth of the crater.

Figure 2.4 is a contour map prepared by A. L. Embry of J-Division, LASL, from the data obtained from the survey made by H&N. Because of the large size of the Mike crater, the original differences in surface contours are less important to the problem than in the case of the Greenhouse shots.

It is pertinent to the results to point out some observations made by the author, which were reported as part of the damage survey on Mike shot.[1] This survey was made about 48 hr after shot time, and numerous pockets of turbid water were observed in the lagoon and ocean at some distances from the main crater and isolated from it by clear water. If this turbid water was due to diffusion from the crater itself, by 48 hr one would expect enough diffusion so that no clear demarkation would exist between the clear and turbid water. On the other hand, this was not the case, and the turbid regions were well separated from the

2C

crater itself. The isolated pockets of turbid water suggested that the crater, even at this time, was still shifting by material flowing through fissures through the coral sheath as suggested in Sec. 1.3.

REFERENCE

1. "Mike Shot Cursory Report," edited by W. E. Ogle and J. H. Lofland, Jr., Appendix A, Los Alamos Scientific Laboratory, November 1952 (not available).

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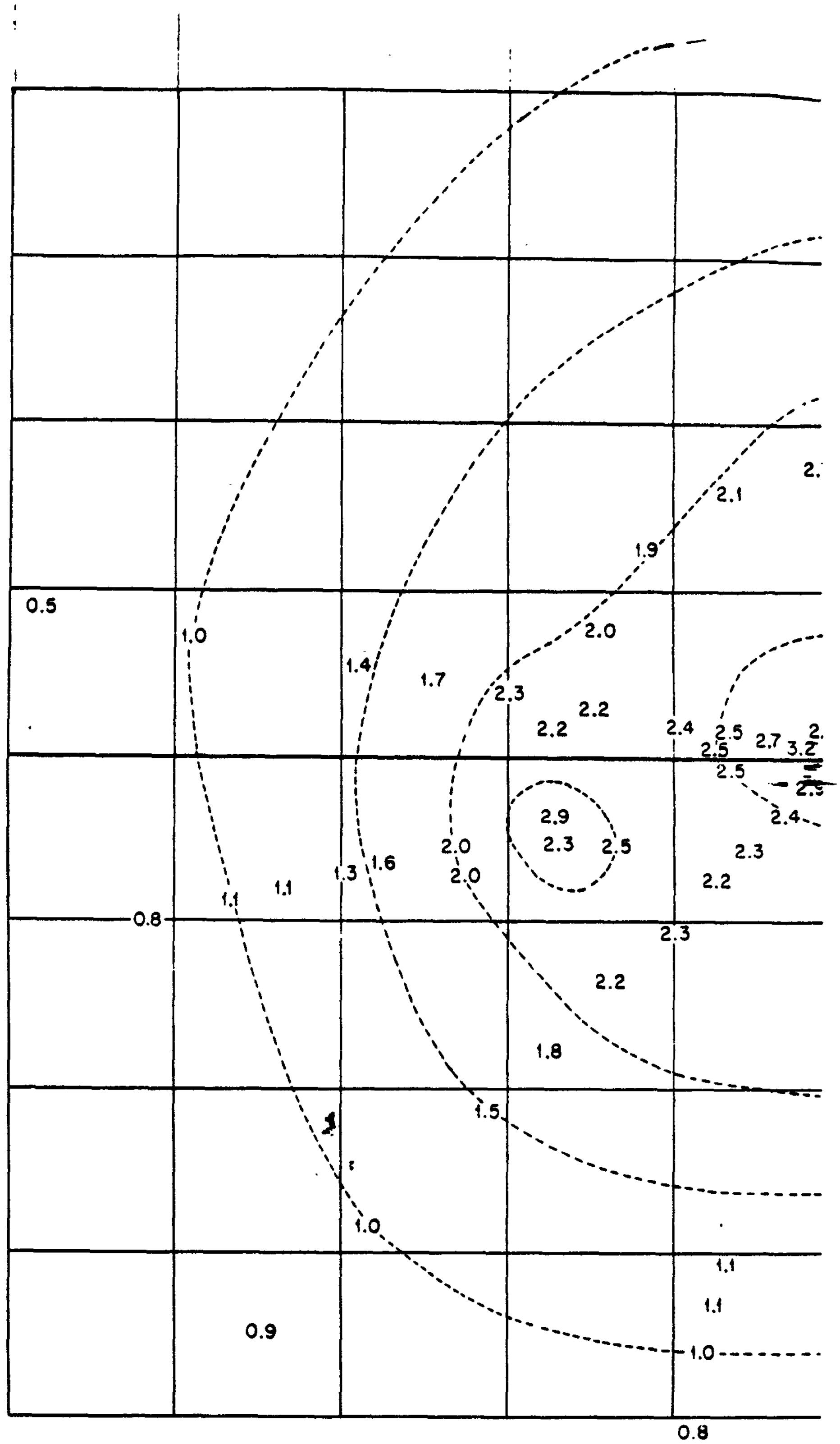
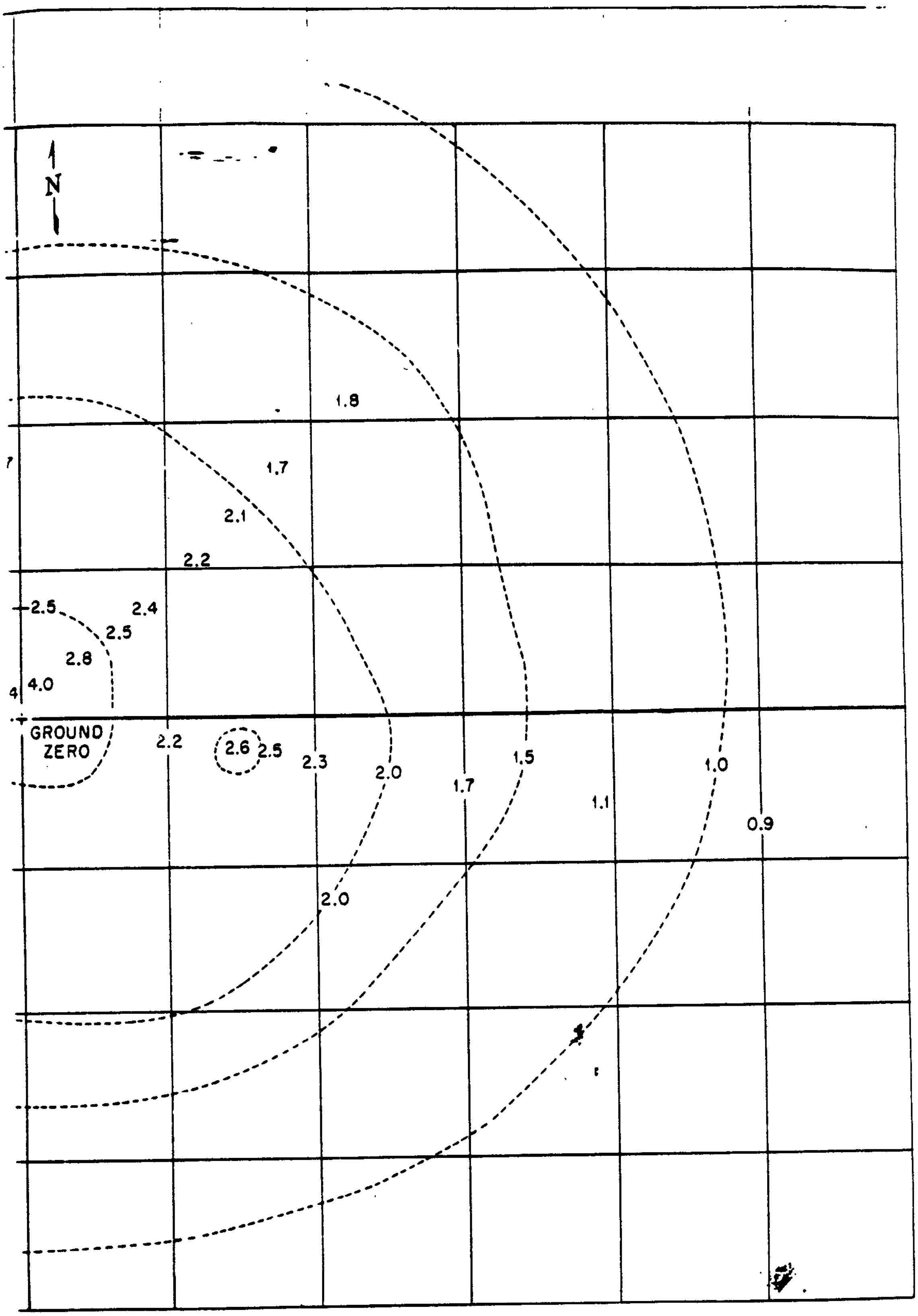


Fig. 2.2 Contour of Crater, Greenhouse Easy Shot. Cc



ntours represent changes in depth in feet. Grid lines are at 100-ft intervals.

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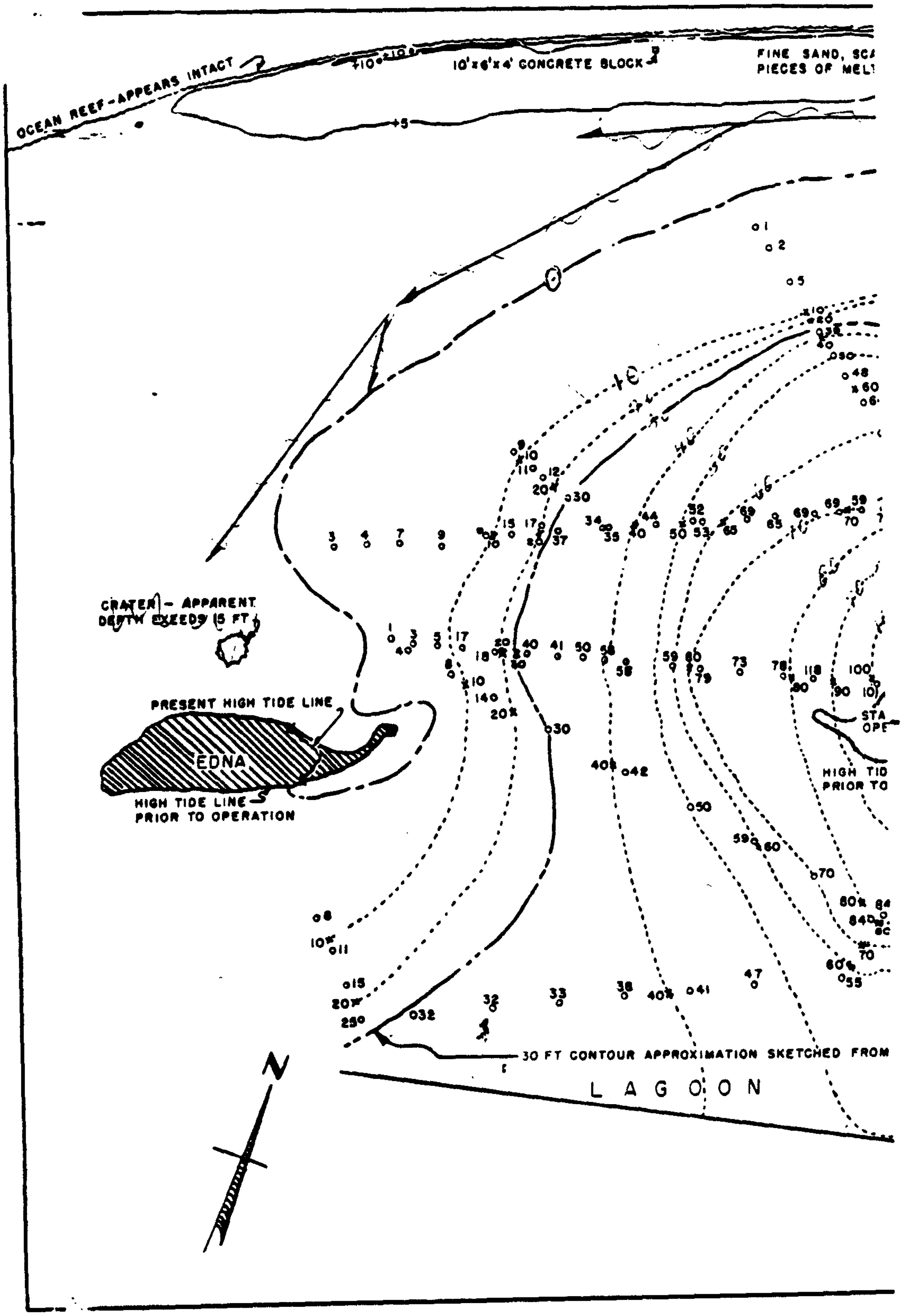
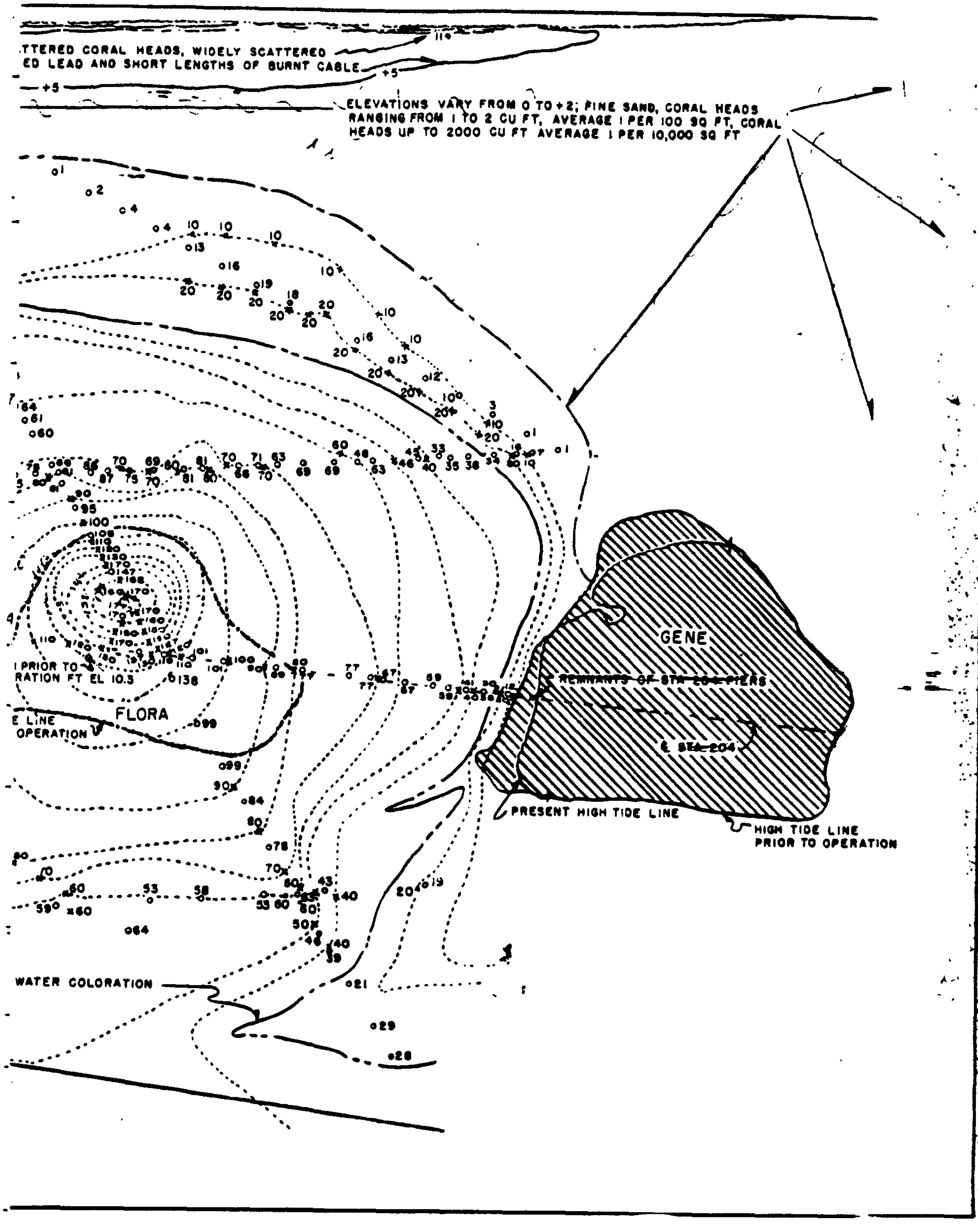


Fig. 2.4 Topograph, Ivy Mike Crater, 2 Weeks
mean low water springs. Present high-tide lines
Approximate



\fter Shot Time. All soundings indicated are in feet below approximate
'ndicated for Edna and Gene were sketched only with no control used.
volume of crater is 1.15 × 10^9 cu ft.

Chapter 3

Discussion

3.1 PROFILES

For discussion, it is somewhat more convenient to present the results of these craters in the form of profiles derived from the contour maps, Figs. 2.1 to 2.4. These profiles appear as dashed lines in Figs. 3.1 to 3.4. On each of these figures the full line is a theoretical line, used for comparison later.

It will be observed on Fig. 2.1 that data were obtained along a number of rays in the Greenhouse Dog crater. Figure 3.1 contains these results as dashed lines, plotted at distances from Ground Zero, and at the various angles indicated by the array of points on Fig. 2.1. The crater is observed to be quite irregular in shape, having a maximum depth apparently less than 3 ft. The existence of mounds in the the effect of the causeway and the deposition of the sand spit south and east of the crater are clearly long-time developments which do not reflect the actual crater shape.

Figure 3.2 is the crater profile from Greenhouse Easy derived from the contour map of Fig. 2.2. This crater is fairly uniform and appears to be reasonably described as a conic section with a maximum depth of about 3 ft, and a crater width of about 600 ft. Isolated elevations determined from the survey are shown as circles on this plot.

Figure 3.3 is the crater profile from Greenhouse George and is fairly regular, considering the processes of erosion and deposition which have occurred since shot time. The high ridge just south of the crater (see Fig. 2.3) is known to have been filled in by bulldozers in order to isolate the lake from the lagoon. Similarly,

Figure 3.4 is the crater profile from Ivy Mike derived from Fig. 2.4, which shows a maximum depth of 170 ft at first glance as the depth of the Mike crater. The interesting point is that the deep hole occurs some 350 ft from Ground Zero. The choice of a pressure profile plot has been made partly to emphasize this fact. From the relative uniformity of the crater at distances beyond 1000 ft, it seems fairly clear that the deep hole is a result of geologic structure. In fact, the 120-ft depth at Ground Zero is influenced to some extent because it lies on the flank of the sink hole. In the absence of this structural weakness, the Mike crater may have been no more than 110 ft instead of the present depth of 120 ft at Ground Zero.

3.2 SIZE AND SHAPE IN CRATER SCALING

In this section the results in Figs. 3.1 to 3.4 are correlated to give a general description for

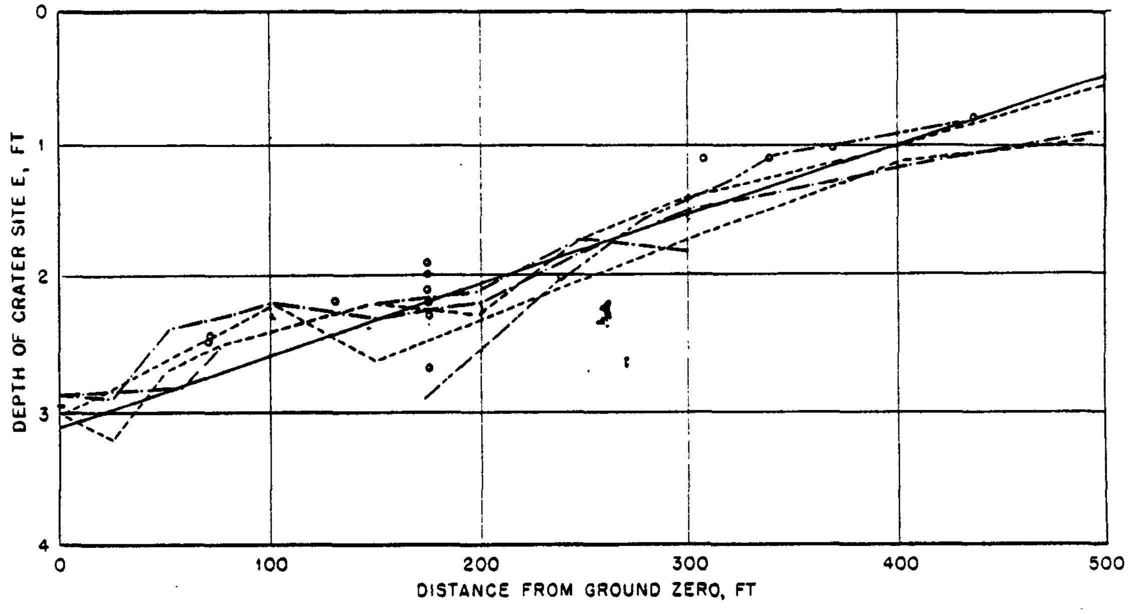


Fig. 3.2 Profiles of Greenhouse Easy Crater. The profiles are measured at distance from Ground Zero, but at random angles, indicated by rays of points on Fig. 2.2.

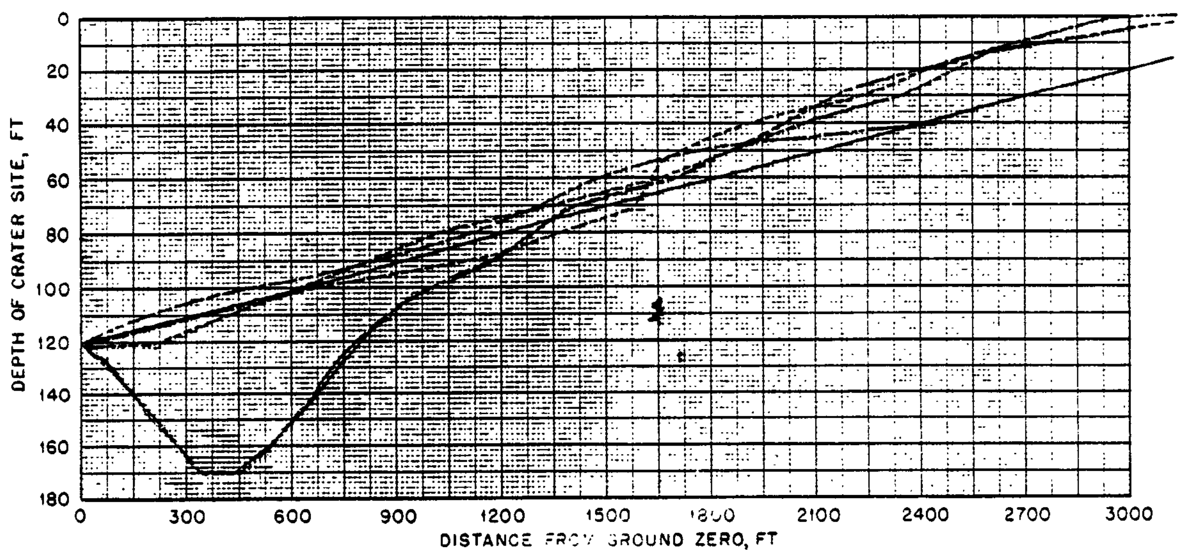


Fig. 3.4 Profiles of Ivy Mike Crater. The profiles are measured from Ground Zero. A hole 170 ft deep occurred about 350 ft from Ground Zero. One ray is plotted through the center of this hole; the three other rays at 90° spacing from this ray. ----, measured along rays 90° apart. ——, theoretical.

craters characteristic of Eniwetok. It will apply only to Eniwetok and is probably influenced strongly by the geologic structure. It can be only a rough description in view of the paucity of experimental points, and because of the mixture of tower and surface shots. Probably neither in magnitude nor shape are the results applicable to other conditions; it can reasonably be hoped for an uncertainty of only a factor of 2 in any general rule which might be deduced.

Figure 3.5 shows an estimate of the crater radii as a function of yield for the four shots. These are fairly certain only on the Greenhouse Easy and Ivy Mike craters, which were set at 600 ft and 3600 ft, respectively. A value of for the Greenhouse Dog crater appears reasonable from the flatness of the profile near , and the choice of for the George crater is supported only by the fact that the high-tide line has been shifted inward to distances like this on the southeast side of the island. A line of slope 1/3 has been passed through these points in such a way that the mean crater radius is expressed in the form

$$R = 160\ W^{1/3}\ \text{ft} \qquad (3.1)$$

where W is in kilotons. The uncertainties are also shown and seem to be of the order of at least 25 per cent, although the questions of fill and sand deposition lead to uncertainties considerably larger than this for the case of Greenhouse Dog and George craters.

Figure 3.6 has a similar plot in which the depths are obtained from Figs. 3.1 to 3.4. On this plot, the depth for Greenhouse Easy crater is fairly certain; the Greenhouse Dog crater is presently more likely too shallow than too deep because of the debris within the crater. Similar remarks apply to the George crater because of the deposition of sand. The Ivy Mike crater has been plotted with an effective depth of 120 ft and regarding the deep hole as a fluctuation introduced by geologic structure. The uncertainty in depth is a factor of 2 as indicated on the figure. A line has been passed through the points in such a way that the maximum depth is expressed by

$$D = \frac{W^{2/3}}{4}\ \text{ft} \qquad (3.2)$$

Owing to variations in the soil, the volume is likely to be a better average than the radius or the depth. Using the fitted expressions for radius and depth, as in Figs. 3.5 and 3.6, assuming the conical shape for theoretical reasons in Sec. 1.1 and with whatever empirical justification occurs in Figs. 3.1 to 3.4, the volume for an Eniwetok crater becomes

$$\text{Volume} = 6700\ W^{4/3}\ \text{ft}^3 \qquad (3.3)$$

The validity of the various assumptions and the fitting process for radius and depth are best judged by an examination of Figs. 3.1 to 3.6, which seem justified within the limits of uncertainty quoted. The volume for the Easy crater has been estimated by the author as 1.13×10^6 cu ft, in comparison with 1.14×10^6 from Eq. 3.3. At the same time, A. L. Embry has estimated the volume of the Ivy Mike crater to be 1.15×10^9 cu ft, in comparison with 1.52×10^9 cu ft from Eq. 3.3, which is considered reasonable agreement. The volumes for Dog and George appear , if anything, but are subject to too great experimental uncertainties to justify a comparison.

3.3 FURTHER RESULTS

Some results of these curves are of interest. Without recourse to a definite comparison, it is clear that the craters from nuclear explosions are much shallower than craters from TNT explosions. For nuclear explosions, the slopes in the craters are in the order of 1 in 200 to 1 in 30, increasing in steepness with larger yields, at least at Eniwetok.

Report LA-1529 was principally concerned with the possibility of triggering a major geologic failure at the Atoll which could, in turn, generate a tsunami of oceanwide proportions.[1] Craters of depths like 100 ft do not involve sufficient volumes to result in such a catastrophe. On the other hand, one would feel considerable concern over a predicted depth of 1000 ft for the crater and, according to Fig. 3.6, this would occur for a surface burst in the order of 250 Mt. However, from Fig. 3.5, the crater radius for such a burst is approximately 2 miles, and the danger could probably be averted for such a large explosion by firing it on a barge in the lagoon 2 miles or more from the reef.

Another item of interest is the high probability of breaching the reef during shot of the Castle series in the spring of 1954. This shot, expected to be in the order of 6 Mt, will

Pages 19 - 20 deleted

have a crater about 3000 ft in radius. It is proposed to fire it on the reef southwest of Namu in Bikini where the reef itself is only approximately 2000 ft wide. The result is of further interest because there presently exists no deep water channel on the north side of Bikini Atoll and the circulation of sea water is confined essentially within the lagoon of the Atoll. The breaching of the reef near Namu will provide the possibility of a deep channel, which may be further deepened by tidal action as the sea water flows in and out of the lagoon. On the other hand, there is also the possibility that the crater will be closed through sand deposition. The result will be interesting, however, because for the first time in history there is a possibility of altering a geographical feature by use of a nuclear explosion.

On Operation Castle a number of shots are to be located on barges several thousand yards offshore within the lagoon, where the water depth is about 30 fathoms, or 180 ft. It seems that no substantial craters will be formed in the lagoon floor for shots on the order of 1 Mt unless the bottom is ooze. If the deep hole in the Mike crater has been correctly attributed to a local geologic structure, and its shape peculiar to its close proximity to the outer edge of the reef, then the depths of Fig. 3.6 are applicable, from which the crater depth over soil itself would be only about 75 ft for shots in the order of 5 Mt. Because the hydrodynamics are such a strong function of the relative density between air and either soil or water at the interface, it would appear reasonable that the crater "in water" will not extend to a depth which is greatly different from that in soil. Since the depth of the lagoon is considerably beyond the expected depth of the crater in soil, there is a good probability that no crater at all will be observed at the lagoon bottom for these barge shots. In any case, they will be difficult to measure by sounding; the depth will be comparable or small compared with the height of the natural water waves in the Bikini lagoon.

REFERENCE

1. F. B. Porzel, Soil Pressures and Energy Transfer on Mike Shot, Los Alamos Scientific Laboratory Report LA-1529, October 1952.

Chapter 4

Conclusions and Recommendations

4.1 CONCLUSIONS

On the basis of previous results and discussions, it is concluded that

1. Craters on Eniwetok Atoll may be roughly described as conical sections with depth, radius, and volume given approximately by the equations in Sec. 3.2.
2. Crater formations at Eniwetok Atoll are significantly affected not only by local soil characteristics but probably by the major geological structure of the Atoll.
3. The completely different phenomenology involved in nuclear explosions in comparison with TNT denies any justification for attempting to scale to correlate the results of TNT with nuclear explosions short of the detailed considerations of the very different early hydrodynamic history of each explosion.
4. From the relatively small size of the craters, it is to be expected that the small energy transfer predicted in Report LA-1529 is confirmed.[1] No major danger from a nuclear explosion through production of a tsunami is expected for bursts under several hundred megatons, and, in this case, it is possible to alleviate the danger by detonation on a barge in the lagoon.

4.2 RECOMMENDATIONS

It is recommended that

1. Surveys similar to those performed for Greenhouse and Ivy are probably worth the effort on future major shots, since they require little more than standard surveying techniques.
2. Since the dynamic behavior of crater formation has not been determined, some further insight can probably be gained by an attempt to measure one crater as soon as possible after zero time.
3. Future crater studies at Eniwetok should consider details of geologic structure in interpreting the data.

REFERENCE

1. F. B. Porzel, Soil Pressures and Energy Transfer on Mike Shot, Los Alamos Scientific Laboratory Report LA-1529, October 1952.

Appendix A

Memorandum for: CTU 3.1.7

From: CTU 3.1.1

Subject: CRATER SURVEYS—ALL SITES LESS E+

Reference: SDF-649

The crater surveys being conducted by Holmes and Narver will consist of detailed surveys of the tower areas to determine the shape and size of the craters and determinations of the amount of material removed and the earth movement produced by the blasts. To facilitate the latter, a number of reference points will be required which will consist in part of existing structures to which should be affixed a reference mark, and the remainder are to be steel survey stakes.

Iron structures imbedded in the concrete of existing structures can serve as the reference, or in case this is impractical, a gun-driven slug flush with the surface may be used. Any markings on the metal or concrete should not be depended on to remain after the shot. The steel stakes are to be of solid steel stock approximately 2 in. in diameter and 4 ft long with a pointed end. These should have an identity mark at about the mid-point of the stake. They are to be driven flush with the ground surface and such that the deflection from the vertical may be measured to ±5 degrees, by use of gunner's quadrant or leveling protractor when the stake has been driven at least 2 ft into the ground. The position and elevation from Ground Zero are to be measured to ±0.01 ft.

On the postshot surveys, the distance by which the stake protrudes is also to be measured to estimate the earth removal. As some time will elapse between shot and survey, during which time there may be some erosion, the exposed portion of the stake should be painted as soon after the shot as possible and the painted length measured at a later date. The inclination of the stakes from the vertical is to be measured on postshot surveys.

The approximate positions of the stakes together with existing structures which may be useful in the surveys are:

SITE C

Stake positions:

On a line 113° to Ground Zero:
at 25, 50, 75, 100, 150, 200, 250, 300, 400, and 500 ft

On a line 293° to Ground Zero:
at 25, 50, 75, 100, 150, 200, 250, 300, 400, and 500 ft

On a line 210° to Ground Zero:
at 25, 50, 75, 100, 150, 200, 250, and 300 ft

On a line 345° to Ground Zero:
at 25, 50, 75, 100, 150, 200, 250, 300, 400, and 500 ft

Stations to be located:

- 27a, b, c, d
- 33a, b, c, d
- 34a, b, c, d
- Tower base (use tower legs for bench mark)
- Cable anchors
- Messenger cable anchors

SITE V

Stake positions:

On a line 190° to Ground Zero:
at 300, 350, 400, 450, 500, and 550 ft

On a line 94° to Ground Zero:
at 300, 350, 400, 450, 500, 600, 700, 850, 1000, 1150 ft

On a line 314° to Ground Zero:
300, 350, 400, 450, 500, 600, 700, 850 ft

Stations to be located:

- 50a
- 51a
- 8
- 145
- 144b
- Tower cable anchors
- Messenger cable anchors

SITE E

Stake positions:

On a line 100° to Ground Zero:
at 25, 50, 75, 100, 150, 200, 250, 300, 400, and 500 ft

On a line 225° to Ground Zero:
at 25, 50, 75, 100, 150, 200, 250, and 300 ft

On a line 45° to Ground Zero:
at 25, 50, 75, 100, 150, 200, 250, 300, 400, and 500 ft

On a line 290° to Ground Zero:
at 100, 150, 200, 250, 300, 400, and 500 ft

Stations to be located:

- 27a, b, c, d
- 33a, b, c, d, e, f, g, h, i
- 34a, b, c, d, e, f
- 121a, b, c, d, e
- 143 (center of pit)
- Tower base (use tower legs for bench mark)
- Cable anchors
- Messenger cable anchor

The preshot work will require about 3 days for a four-man survey crew plus three laborers for setting the stakes for each survey.

As soon as radiologically feasible, approximately 5 to 10 days after each shot, two to four men working in relays accompanied by a monitor will be required to paint a stripe to mark the amount of each exposed stake. This should require about $1\frac{1}{2}$ hr.

When radiologically feasible, the complete crater surveys are to be done as stated above. These will require a four-man survey crew to work approximately 5 days per shot. A monitor will be required at these times, which may be 1 to 4 months after the shots. Two laborers are to accompany the crews after the surveys. The damaged stakes, together with their locations, are to be part of the data.

It should be realised that time estimates given above are highly dependent upon severity of radiological contamination in the tower area and hence highly optimistic.

Logistic support and monitors must be furnished to the working crews.

Memorandum for:	CTU 3.1.7
From:	CTU 3.1.1
Subject:	CRATER SURVEYS, ALL SITES LESS E+
Reference:	SDF-2181

The following procedure is to be considered an elaboration of SDF-649, dated 20 March 1951:

1. Determine elevation of undisturbed ground in immediate vicinity of each stake.
2. Determine, with maximum feasible field accuracy, direction with respect to Ground Zero of bent portion of all stakes.
3. File reference mark on all stakes at bend.
4. Determine elevation of above reference mark for all stakes.
5. Establish by survey, postshot position of all stakes to accuracy consistent with accuracy of preshot stake survey.
6. Completely excavate nearest-in stake and one medium-distance stake on each line.
7. If the two stakes specified in Step 6 are straight below the top bend, pull carefully the remaining stakes in the line.
8. If the two stakes specified in Step 6 are not straight below the top bend, excavate carefully all stakes up to radial distances where the stakes become straight below the top bend.
9. Attach to all stakes tags indicating preshot location (distance and azimuth to Ground Zero) and ship stakes, together with all above data, to: Edward J. Zadina, Los Alamos Scientific Laboratory, P.O. Box 1663, Los Alamos, N. Mex.

Appendix B

CRATER SURVEY, SITE C

The following tabulations consist of data requested in AEC Work Order No. 575, Operation Greenhouse, and AEC Work Order No. 10 of tʰ current operation.

Table B.1 contains the data obtained for the 4-ft lengths of 3-in pipe. These were recovered during the completion of the survey work, 10 March 1952 to 12 March 1952. The pipes were delivered to the Warehouse Department for shipment to Edward J. Zadina, Los Alamos Scientific Laboratory, P. O. Box 1663, Los Alamos, N. Mex.

The following explanations apply to the columns in Table B.1.

Column 2

The crater survey stakes are indicated by a number followed by a dash and the letter "C." The numbering follows the order of listing in letter SDF-649 up to and including number 27-C. The next in order was assigned 28C-28C; the remainder are in sequence from 28-C to 37-C. The recovered stakes are tagged in accordance with the above.

Columns 3 and 4

preblast distance from Ground Zero was [illegible] red to the center of the stake. The post-[illegible] measurement was made to the approximate center of the straight portion. The distance and azimuth were taken to the same point.

Column 5

The postblast ground elevations were taken on 17 July 1951.

Column 7

The deflection of the bent portion of the stake is reckoned clockwise from the line from the stake to Ground Zero.

Column 8

The deflection of the straight portion of the stake is from a vertical line through the bottom of the straight portion.

pages 27 & 28 deleted.

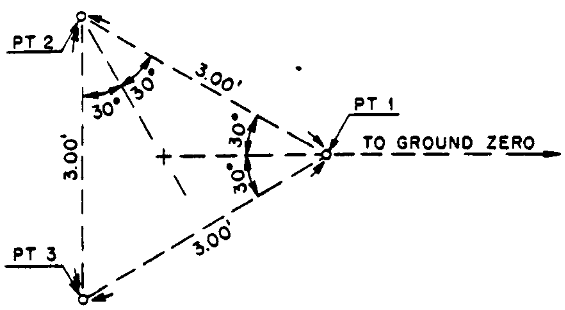
The following explanations apply to the columns in Table B.2.

Column 1

The station numbers are for Operation Greenhouse.

Column 2

The points (Pt. 1, 2, and 3) are indicated in the following sketch.



Column 6

The postblast ground elevations were taken on 17 July 1951.

Column 7

A reference mark was filed on the 33 and 34 stakes at the approximate top of the straight portion of the stake, diametrically opposite to the direction of bend. All 33 and 34 stakes are bent 180° from Ground Zero.

Column 8

The original working point (W.P.) was reestablished, and the distance was measured from this point to the approximate center of the straight portion of each stake.

Column 9

The length of bend was measured from the reference mark, column 7, along the outside curve to the end of the stake.

Column 10

The horizontal length of bend is the horizontal distance from a vertical line through the reference mark, column 7, to the end of the stake.

TABLE B.2 CRATER SURVEY, SITE C

		Preblast		
Sta. No.	Pt.	Distance, W.P. from Ground Zero (ft)	Azimuth of W.P. to Ground Zero	Elev., Top of Stake (ft)
(1)	(2)	(3)	(4)	(5)
34a	W.P.	280.05	261°30'02"	
	1			10.32
	2			10.31
	3			10.43
34b	W. P.	309.05	261°30'02"	
	1			10.18
	2			10.16
	3			10.13
34c	W.P.	339.07	261°30'02"	
	1			9.69
	2			9.67
	3			9.59
34d	W.P.	369.10	261°30'02"	
	1			8.90
	2			8.94
	3			8.94

TABLE B.2 (Continued)

		Preblast		
Sta. No.	Pt.	Distance, W.P. from Ground Zero (ft)	Azimuth of W.P. to Ground Zero	Elev., Top of Stake (ft)
(1)	(2)	(3)	(4)	(5)
33a	W.P.	15.00	81°30′02″	
	1			9.38
	2			9.39
	3			9.38
33b	W.P.	69.00	81°30′02″	
	1			9.50
	2			9.50
	3			9.50
33c	W.P.	171.00	81°30′02″	
	1			9.47
	2			9.47
	3			9.47
33d	W.P.	240.00	81°30′02″	
	1			9.18
	2			9.17
	3			9.18
33e	W.P.	279.00	81°30′02″	
	1			8.95
	2			8.95
	3			8.95
33f	W.P.	309.00	81°30′02″	
	1			8.82
	2			8.82
	3			8.82
33g	W.P.	338.98	81°30′02″	
	1			8.65
	2			8.64
	3			8.65
33h	W.P.	368.95	81°30′02″	
	1			8.09
	2			8.08
	3			8.08
33i	W.P.	399.96	81°30′02″	
	1			7.09
	2			7.09
	3			7.07

* Stakes were straight.
† Values are inclination from vertical.

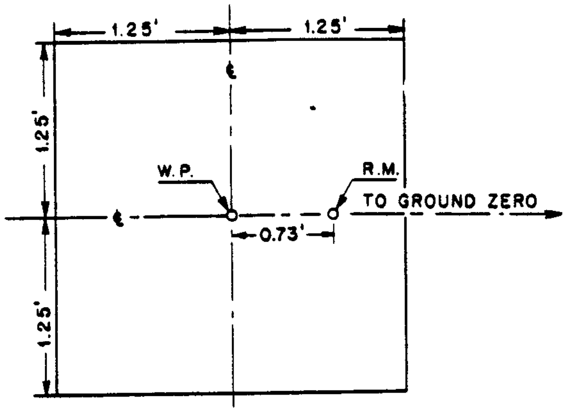
The following explanations apply to the columns in Table B.3.

Column 1

The station numbers are for Operation Greenhouse.

Column 2

The distance of working point to Ground Zero is indicated in the following sketch.



Column 4

The preblast elevation of reference mark (R.M.) was taken at a point indicated in the foregoing sketch, on the 3-in. steel plate.

Column 5

The postblast ground elevations were taken 17 July 1951. Station 27a was not located at that time.

Column 6

The postblast distance of the working point to Ground Zero was taken to approximately the same point as the preblast distance. All four concrete blocks were damaged by the blast.

Column 7

The postblast elevation of the reference mark (R.M.) was taken to a point on the concrete block approximately 0.73 ft from the working point. The steel plates were missing from all four stations.

TABLE B.3 CRATER SURVEY, SITE C

	Preblast		
	To Ground Zero		
Station	Distance (ft)	Azimuth	Elev. of R.M. (ft)
(1)	(2)	(3)	(4)
27a	12.00	83°50′02″	9.32
27b	68.97	83°50′02″	9.42
27c	170.94	83°50′02″	9.47
27d	240.00	83°50′02″	9.04

CRATER SURVEY, SITE E

The crater survey pipes were delivered to Holmes and Narver warehouse department 21 May 1952 with a request for shipment to Edward J. Zadina, Los Alamos Scientific Laboratory, P.O. Box 1663, Los Alamos, N. Mex.

The postblast data were observed from 28 April 1952 to 12 May 1952. The following explanations apply to the columns in Table B.4.

Column 2

The numbering of the stakes follows the order of listing in letter SDF-649 (Appendix A). The recovered stakes are tagged to correspond.

Column 3

The azimuth is reckoned at the stake, from north clockwise to Ground Zero.

Column 4

Distance is measured from Ground Zero to the center of the stake. All distances and elevations are in feet.

Column 5

Preblast elevation was taken on the top of stake which was flush with surface. Postblast elevation was taken on the surface by stake.

Column 6

A file mark was made at the approximate point of bend and the elevation recorded.

Column 7

Bent deflection is reckoned clockwise from the line from the stake to Ground Zero, to the end of the bent portion.

Column 8

Straight deflection is reckoned from a vertical line through the bottom of the straight portion of pipe.

[redacted]

The following explanations apply to the columns in Table B.5.

Column 1

Station numbers are for Operation Greenhouse.

Column 2

The stakes are numbered as shown in the accompanying sketch of the preblast layout for Stations 33 and 34. All stakes are straight and lean away from zero except 33a and 33c which were damaged during the postblast cleanup operations.

Column 3

Distance is from the working point to Ground Zero (see sketch).

Column 4

Azimuth is reckoned at the working point, from North clockwise to Ground Zero.

Column 5

The elevation of the top of the stake prior to the blast.

Column 6

The elevation of the top of stake subsequent to the blast.

Column 7

The distance is from the working point to the center of the stake.

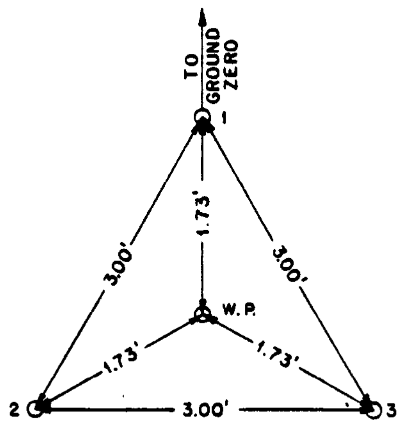


TABLE B.5 CRATER SURVEY, SITE E

		Preblast		
Station	Stake	Distance, W.P. from Ground Zero (ft)	Azimuth of W.P. to Ground Zero	Elev., Top of Stake (ft)
(1)	(2)	(3)	(4)	(5)
33a	W.P.	15.00	202°17'15"	
	1			7.52
	2			7.53
	3			7.51
33b	W.P.	69.00	93°09'45"	
	1			7.20
	2			7.22
	3			7.19
33c	W.P.	171.00	76°00'00"	
	1			7.65
	2			7.62
	3			7.64
33d	W.P.	240.00	76°00'00"	
	1			8.33
	2			8.34
	3			8.34

TABLE B.5 (Continued)

Station	Stake	Preblast: Distance, W.P. from Ground Zero (ft)	Preblast: Azimuth of W.P. to Ground Zero
(1)	(2)	(3)	(4)
33e	W.P.	279.00	76°00′00″
	1		
	2		
	3		
33f	W.P.	309.00	76°00′00″
	1		
	2		
	3		
33g	W.P.	339.00	76°00′00″
	1		
	2		
	3		
33h	W.P.	369.00	76°00′00″
	1		
	2		
	3		
33i	W.P.	429.00	76°00′00″
	1		
	2		
	3		
34a	W.P.	309.00	13°39′12″
	1		
	2		
	3		
34b	W.P.	339.00	13°39′12″
	1		
	2		
	3		
34c	W.P.	369.00	13°39′12″
	1		
	2		
	3		
34d	W.P.	429.00	13°39′12″
	1		
	2		
	3		

* Stake lying on the ground; not in original postblast position.

The following explanations apply to the columns in Table B.6.

Column 1

The station numbers are for Operation Greenhouse.

Column 2

Azimuth is reckoned at the station clockwise from North to Ground Zero.

Column 3

Distance is from working point to Ground Zero.

Column 4

Elevation taken on corner of cover plate, Stations 27a to d, except as noted; on foundation of Stations 121a to e.

Column 5

Elevation taken at approximately same point as preblast elevation.

TABLE B.6 CRATER SURVEY, SITE E

	W.P. to Ground Zero		
Station	Azimuth	Distance (ft)	Preblast Elevation (ft)
(1)	(2)	(3)	(4)
27a	191°38′16″	12.00	7.57
27b	90°00′00″	69.00	7.19
27c	73°39′12″	171.00	7.71
27d	73°39′12″	240.00	8.38
121a	96°00′00″	175.00	7.52
121b	116°00′00″	175.00	7.44
121c	136°00′00″	175.00	7.34
121d	156°00′00″	175.00	7.43
121e	176°00′00″	175.00	7.47

* Cover gone; elevation on concrete block.