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# EXPLOSIVE DITCHING WITH TNT

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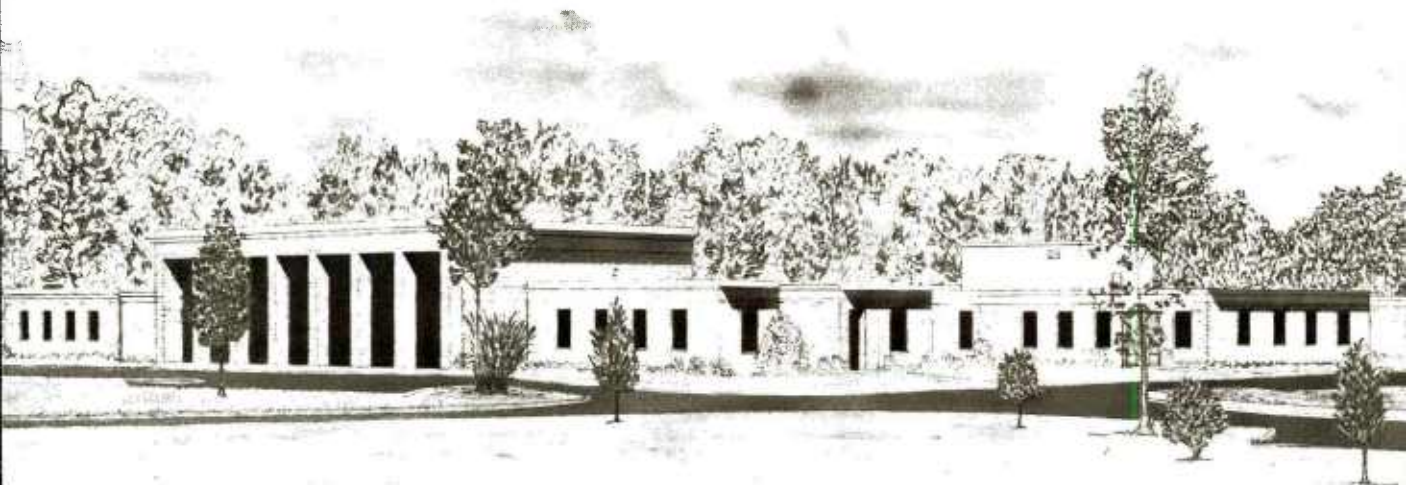
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Weapons Effects Laboratory  
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P. O. Box 631, Vicksburg, Miss. 39180

July 1977  
Final Report

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Errata Sheet

No. 1

EXPLOSIVE DITCHING WITH TNT

Miscellaneous Paper N-77-7

July 1977

1. The equation in line 10, page 41, should read as follows:

$$n = \left( \frac{L}{S} \right) + 1 = \frac{2000}{5} + 1 = 401$$

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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>This report enables the comparison of data being developed on new commercial explosives with the military standard TNT explosive. The report presents the current definitions for single and row craters and the soils and rocks classification system for explosive excavation purposes.<br><br>The theoretical basis for predicting and designing excavations by means of explosives is developed. Field data for nine different media were reexamined and submitted to a statistical analysis following preestablished criteria.<br><p style="text-align: right;">(Continued)</p> |                       |   |  |

20. ABSTRACT (Continued).

The results of this analysis, along with the parameters for optimum charge burial depth for each medium, are presented in graphic form. Smoothness conditions are established for ditching designs, and some sample calculations of single and row craters are presented. Appendixes A and B present crater dimensions from single high-explosive charge detonations in rock and in soil, respectively. Appendix C gives ditch dimensions from high-explosive row-charge detonations in rock and soil.

## PREFACE

This study was conducted during FY 1976 and the T-Quarter under the sponsorship of the Office, Chief of Engineers, U. S. Army, as a part of the Military Engineering Applications of Commercial Explosives (MEACE) program under Project 4A762719AT40, "Mobility, Soils, and Weapons Effects Technology," Task A1, Work Unit 012. Because of the importance of the explosive TNT as a standard for cratering studies, a meticulous reexamination was made of all available TNT data. These data were converted to the metric system of measurement to allow their direct comparison with data being developed on newer explosives during field tests of the MEACE program. Finally, a uniform application of appropriate computer techniques was made to all of the TNT data. This report has been formatted to be of maximum usefulness to field engineers.

MAJ Arno M. Müller, a Brazilian exchange officer assigned to the Explosive Excavation Division (EED), Weapons Effects Laboratory (WEL), U. S. Army Engineer Waterways Experiment Station (WES), conducted the study and wrote this report under the supervision and with the assistance of Mr. H. D. Carleton, EED, Project Manager for the MEACE program.

Chiefs of EED during the study were MAJ L. C. Webster and Mr. J. W. Brown; Chief of WEL was Mr. W. J. Flathau.

Directors of WES during the conduct of this study and the preparation and publication of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, METRIC (SI) TO U. S. CUSTOMARY AND  
U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

Units of measurement used in this report can be converted as follows:

| Multiply                              | By        | To Obtain                      |
|---------------------------------------|-----------|--------------------------------|
| <u>Metric (SI) to U. S. Customary</u> |           |                                |
| millimetres                           | 0.03937   | inches                         |
| metres                                | 3.28084   | feet                           |
| cubic metres                          | 35.31467  | cubic feet                     |
| kilograms                             | 2.20462   | pounds                         |
| metres per kilogram <sup>1/3.0</sup>  | 31.8      | feet per ton <sup>1/3.0</sup>  |
| metres per kilogram <sup>1/3.2</sup>  | 27.6      | feet per ton <sup>1/3.2</sup>  |
| metres per kilogram <sup>1/3.4</sup>  | 24.3      | feet per ton <sup>1/3.4</sup>  |
| kilopascals                           | 0.1450377 | pounds (force) per square inch |

|                                       |           |             |
|---------------------------------------|-----------|-------------|
| <u>U. S. Customary to Metric (SI)</u> |           |             |
| inches                                | 2.54      | centimetres |
| pounds (mass)                         | 0.4535924 | kilograms   |

# EXPLOSIVE DITCHING WITH TNT

## PART I: INTRODUCTION

### Purpose and Scope

1. This report is a guide to the calculation and positioning of TNT charges for cratering and ditching purposes. It is intended to summarize in one publication all information necessary for the prediction and design of TNT craters in a variety of earth materials. Since the included design methods are empirically based, the number of earth media to be included has necessarily been based upon the availability of experimental data.

### Background

2. Since the first systematic investigations of the cratering effects of large TNT charges began during World War II, a variety of cratering tests have been conducted. The earliest experiments were concerned primarily with the effects of bomb detonations near structures. These early tests led in the late 1940's to the U. S. Army Corps of Engineers Underground Explosion Test Program involving spherically stacked TNT charges in a variety of earth media. Emphasis in these later tests was placed upon the development of design criteria for explosion-resistant underground structures. Also in the late 1940's, a series of TNT cratering tests, the Panama Canal Company's Isthmian Canal Study, was conducted in the Panama Canal Zone to determine the Canal's vulnerability to attack by nuclear weapons.

3. TNT cratering tests continued to be an important part of weapons effects studies into the 1950's and 1960's. In addition, TNT cratering and ditching tests were the predominant experiments during the early stages of the U. S. Atomic Energy Commission's Plowshare Program in the 1960's. Though a shift to other chemical explosives for ditching

experiments began during the 1960's and has continued since, TNT is still the only explosive that has a data base broad enough to establish it as a standard for the evaluation of all other cratering explosives.

### Cratering Definitions

4. The following definitions, most of which are illustrated in Figure 1, are commonly used in explosive excavation literature.<sup>1-3</sup>

- a. True crater. The boundary of the crater representing the limit of dissociation of the medium by the explosion.
- b. Apparent crater. Portion of the visible crater below the original ground surface elevation.
- c. Apparent lip. Portion of the visible crater above the original ground surface elevation. It is composed of two parts: upthrust (true lip) and ejecta.
- d. Upthrust. Material that has been permanently displaced above the original ground surface elevation.
- e. Ejecta. Material permanently ejected from the true crater void by the explosion.

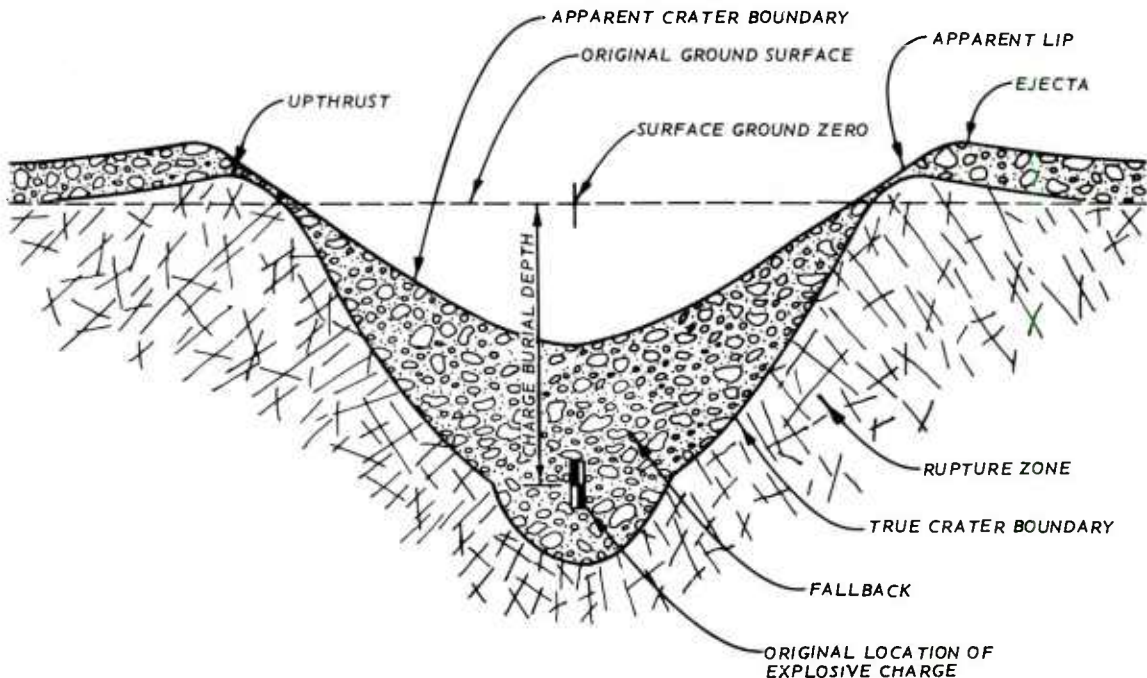


Figure 1. Cross section of typical crater in rock, showing nomenclature

- f. Fallback. Material dissociated by the explosion that has fallen back within the true crater void.
- g. Rubble. Material comprising the fallback and ejecta.
- h. Rupture zone. The zone of blast-induced fractures and displacement from true crater boundary outward to the relatively undisturbed in situ material.
- i. Charge burial depth. The emplacement depth at which the charge is fired.
- j. Optimum charge burial depth. The emplacement depth that produces the largest possible crater.
- k. Row shot. A multiple explosion with the charges emplaced in a linear array (row of charges).
- l. Row crater. A ditch or canal formed by the detonation of charges emplaced in a row shot geometry.

#### Influence of Charge Burial Depth on Crater Formation

5. From the cratering standpoint, the charge burial depth\*  $B$  is the distance from the center of mass of the charge to the original ground surface. For a given weight of charge, variation in the charge burial depth will result in craters of differing shapes and dimensions. A surface burst ( $B = 0$ ) forms a shallow depression by crushing, compacting, and scouring the material below the explosion (Figure 2a). At a shallow  $B$  the material is thrown out with high velocity, increasing the ejecta volume, and very little material falls back (Figure 2b). When the maximum amount of material is thrown out of the crater and maximum crater dimensions are reached, the corresponding burial depth will be the optimum (Figure 2c). Below this optimum  $B$ , a larger quantity of material will be disturbed, but very little of it will be ejected; instead, a crater mound will result from fallback (Figure 2d). If  $B$  is increased to the depth at which no fragmented material is thrown out, the contained explosion will create a cavity by compaction and collapse of the disturbed material (Figure 2e).

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\* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix D).

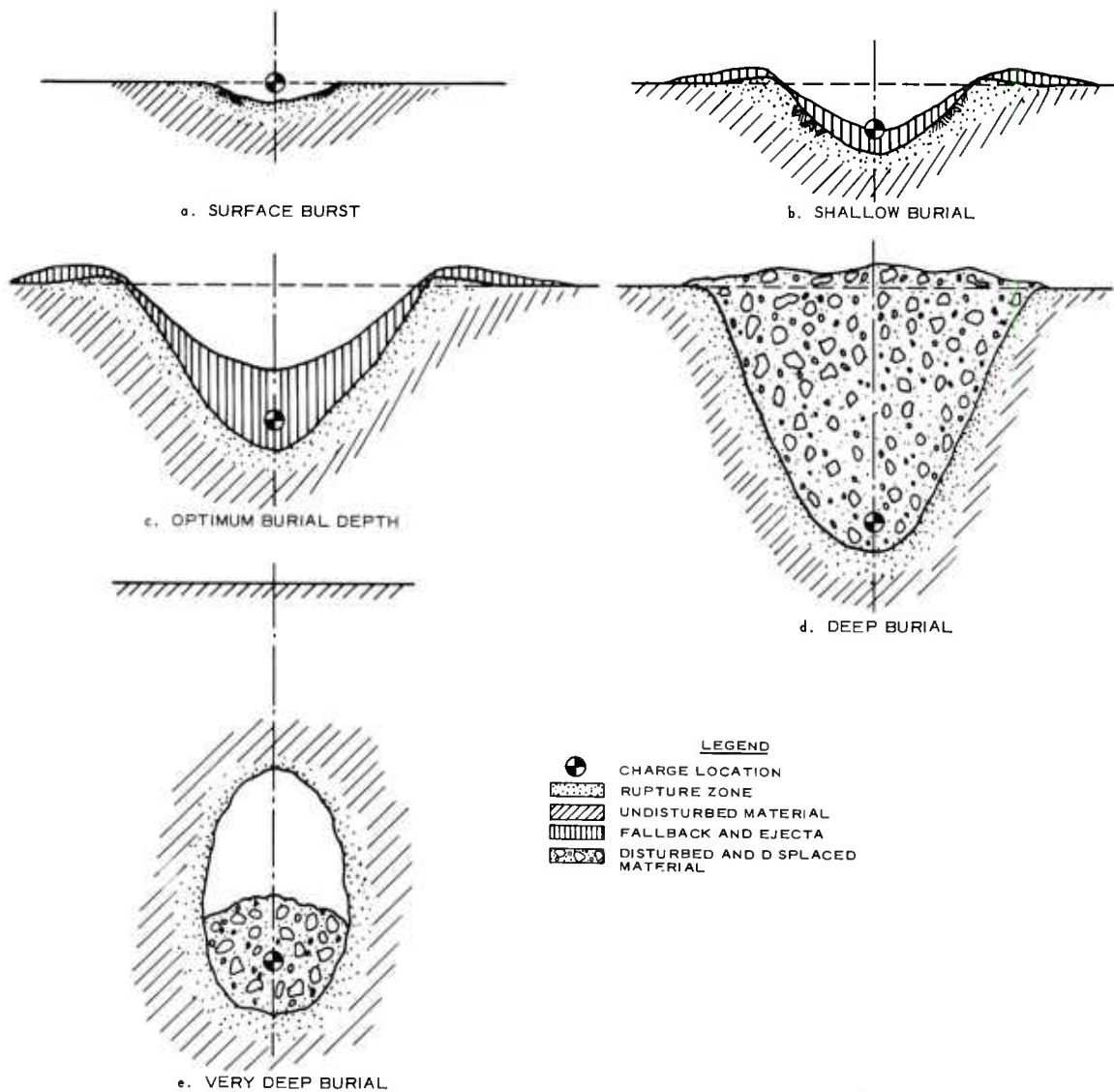


Figure 2. Crater profiles as a function of burial depth for the same weight of charge

## Classification of Cratered Media

6. The available media classification system for explosive excavation in rock<sup>4,5</sup> and the Unified Soil Classification System<sup>6</sup> were used as much as possible to define the media for which data were analyzed in this report (Tables 1 and 2).

7. The following rock and soil types will be covered in this report. An adjective describing degree of saturation has been added to each soil's designation.

| <u>Type</u>                | <u>Classification</u>         |
|----------------------------|-------------------------------|
| <u>Rock</u>                |                               |
| Basalt                     | High-strength rock            |
| Granite                    | High-strength rock            |
| Sandstone                  | Intermediate-strength rock    |
| Weak sandstones and shales | Weak rock                     |
| <u>Soil</u>                |                               |
| Dry gravelly sand          | Coarse-grained soil (GW)      |
| Dry sand                   | Coarse-grained soil (*)       |
| Dry sandy clay             | Coarse-grained soil (SC)      |
| Wet clay                   | Fine-grained soil (OH and MH) |
| Saturated silty clay       | Fine-grained soil (*)         |

\* Gradation, plasticity index, and liquid limits unknown.

## PART II: SINGLE-CRATER DESIGN

8. Criteria for the design of single craters by the use of empirical scaling relationships are developed in the following paragraphs. While single-crater design may be an object in itself, it is more likely in engineering applications that ditching designs will be desired. This part therefore derives its primary importance from the fact that single-crater design is basic to explosive ditching design.

9. Computer programs are available that use calculations of mound and cavity growth with a free-fall throw-out model to give cratering phenomena predictions. However, the empirical scaling method offers accuracy comparable to that of computerized methods,<sup>3,7</sup> and is much more convenient and suitable for the use of engineers in the field. Discussions in this report will be limited to those necessary to convey to the prospective user an understanding of the empirical scaling method of crater design.

### Theoretical Basis

10. The basic premise of the empirical scaling method is that the ratio between the apparent linear dimensions of two craters caused by the same type explosive in the same medium will be equal to the ratio between the charge weights raised to a power:<sup>8</sup>

$$\frac{x_1}{x_0} = \left( \frac{w_1}{w_0} \right)^{1/a} \quad (1)$$

where

$x_1, x_0$  = linear dimensions of the compared craters

$w_1, w_0$  = corresponding charge weights

$1/a$  = power to which charge weights are raised

For cratering with conventional explosives, the value of  $a$  ranges between 3.0 and 3.4, depending upon the characteristics of the cratered

medium. The value of  $a$  may range up to 4.0 when the cratering effects of nuclear devices are considered.<sup>3,8</sup>

11. By extension of the preceding premise, the ratio between the apparent crater volumes of two craters caused by the same type explosive in the same medium will be equal to the ratio between the charge weights raised to a power equal to three times the power of the corresponding relation for the linear dimensions:

$$\frac{V_1}{V_0} = \left( \frac{w_1}{w_0} \right)^{3/a} \quad (2)$$

where  $V_1$  and  $V_0$  are the apparent crater volumes.

12. Equations 1 and 2 can be rewritten to introduce coefficients as follows:

$$x_1 = c_x w_1^{1/a}, \quad \text{where } c_x = \frac{x_0}{w_0^{1/a}} \quad (3)$$

$$V_1 = c_v w_1^{3/a}, \quad \text{where } c_v = \frac{V_0}{w_0^{3/a}} \quad (4)$$

where

$c_x$  = coefficient for linear crater dimension

$c_v$  = coefficient for apparent volume of single crater

The coefficients  $c_x$  and  $c_v$  and the exponent  $1/a$  can be calculated from experimental data. The coefficients will be different for different media and moisture contents, and for different explosives. Once these coefficients and the exponent become available for any given explosive and medium, however, cratering dimensions or volumes may be predicted for any desired charge weight using the simple relationships:

$$x = c_x w^{1/a} \quad (5)$$

and

$$V = c_v w^{3/a} \quad (6)$$

where  $1/a$ , the exponent, and the  $c$  coefficients are known quantities. Transposing Equations 5 and 6 will also make possible the determination of the charge weights required to produce craters of required sizes:

$$w = \left( \frac{x}{c_x} \right)^a \quad (5a)$$

and

$$w = \left( \frac{V}{c_v} \right)^{a/3} \quad (6a)$$

#### Scaled Dimension Plots

13. The linear dimensions of primary interest for cratering purposes are apparent crater radius  $R$ , apparent crater depth  $D$ , and charge burial depth  $B$ , shown in Figure 3. Coefficients can be computed

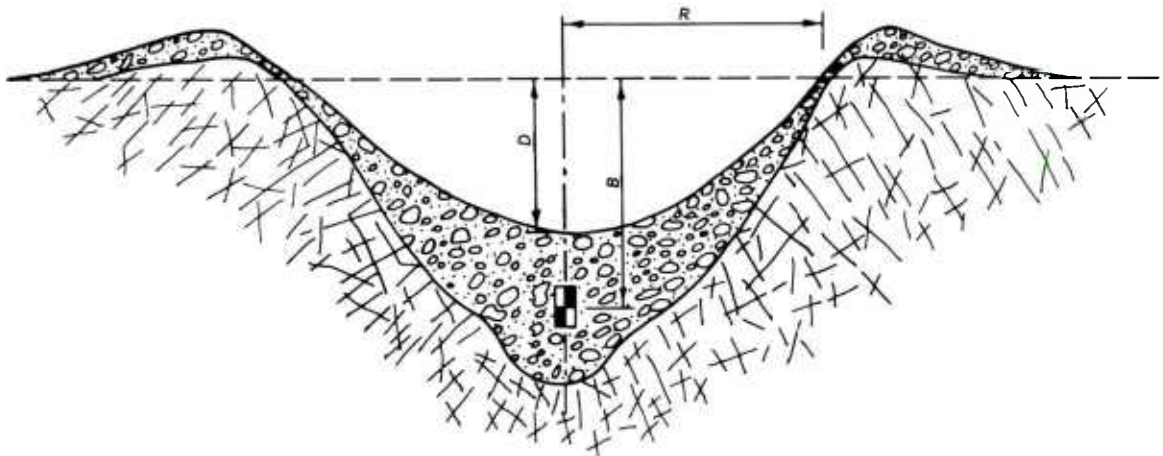


Figure 3. Cross section of a single crater

for  $B$ ,  $R$ ,  $D$ , and  $V$  for each experimental crater that results

from a specific combination of explosive and medium after the manner used for Equations 3 and 4:

$$c_b = \frac{B}{w^{1/a}} \quad (7)$$

$$c_r = \frac{R}{w^{1/a}} \quad (8)$$

$$c_d = \frac{D}{w^{1/a}} \quad (9)$$

$$c_v = \frac{V}{w^{3/a}} \quad (10)$$

These coefficients represent the scaled dimensions of the crater actual dimensions. These computations will allow a direct comparison of the cratering effects from charges of various weights, so that the effects of charge burial depth variation can be isolated and studied. Scaled dimensions for all craters within the group to be studied can be plotted on a Cartesian coordinate system to quantify the manner in which crater dimensions vary with changes in charge burial depths. As an example, the curve in Figure 4 (which represents a low-order polynomial function fitted to experimental data points by a least-squares fit) shows the dependence of scaled apparent radius on scaled charge burial depth for a hypothetical explosive/medium combination that scales at  $a = 3.4$ . The largest possible crater radii for this explosive in this medium will occur at burial depths corresponding to the scaled charge depth value  $c_b$ , indicated by the arrow at the peak of the curve. The prediction for the radius to be achieved by a given charge weight buried at this scaled depth will be based upon the value of  $c_r$  at this point. Both the required burial depth and the predicted crater radius could be calculated from Equation 5 for any given charge weight by appropriate substitution of the values of  $a$ ,  $c_b$ , and  $c_r$  given in Figure 4.

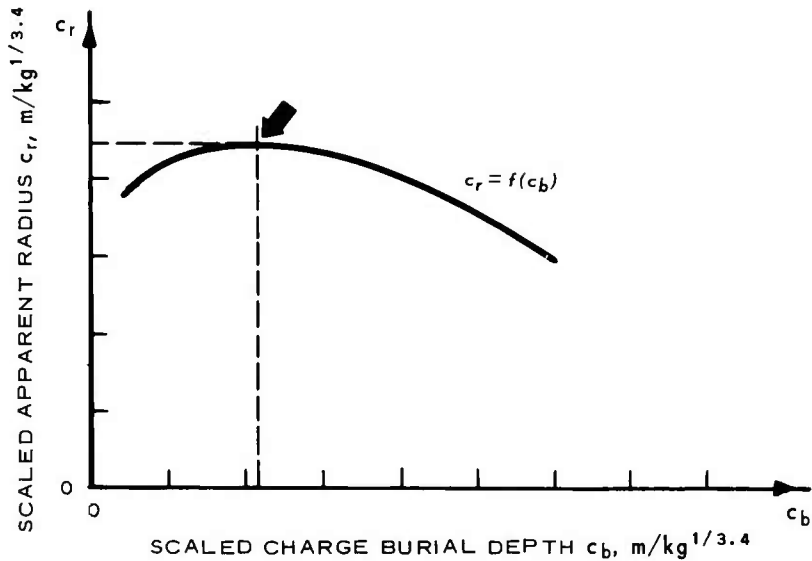
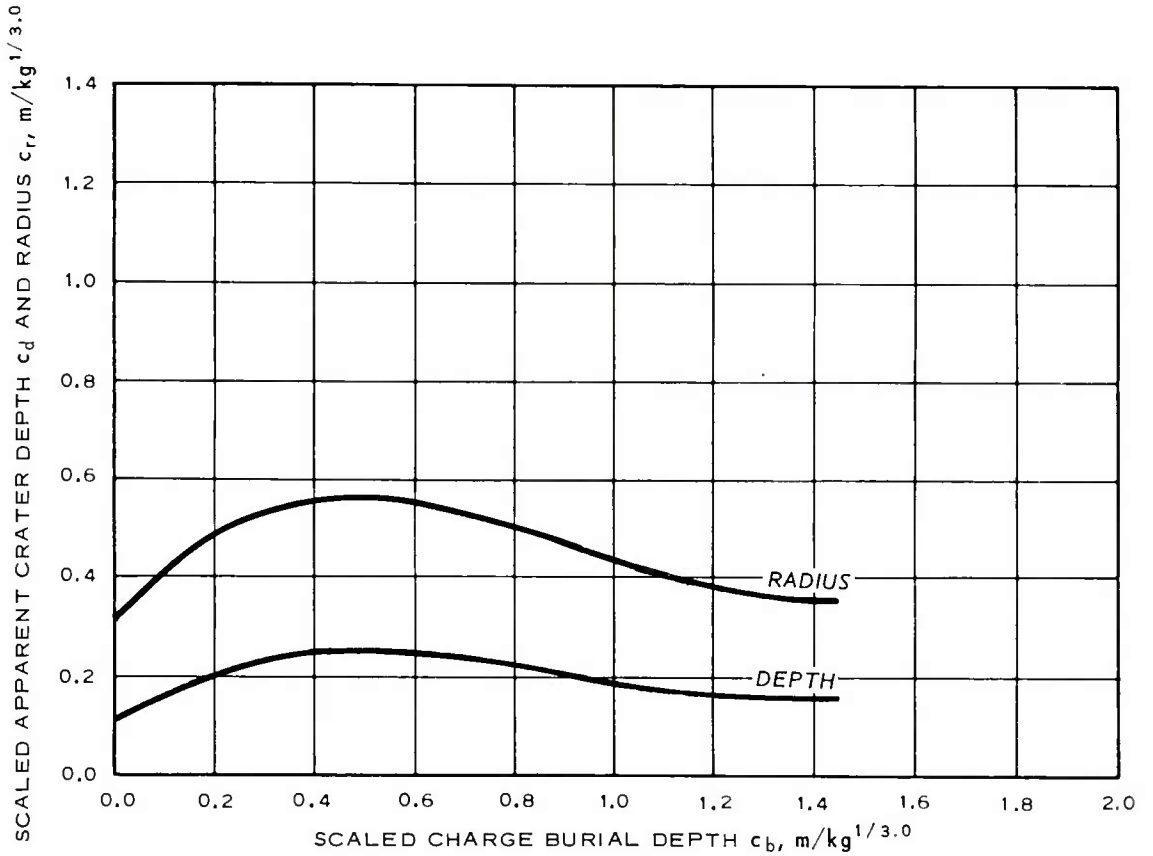


Figure 4. Scaled radius curve for a defined explosive and medium for which  $a = 3.4$

#### Cratering Curves

14. Appendixes A and B list all high-explosive single-crater data available from the references listed in this report. A statistical regression analysis has been performed on the TNT data from these appendixes to produce data plots for nine media (Figures 5-13). There are two plots for each medium: (a) a scaled dimension plot (similar to that discussed in paragraph 13) on the left-hand page, and (b) a design chart on the right-hand page of the two-page spread for each medium. Each design chart graphically relates charge weights on the abscissa to crater dimensions and volumes on the ordinate; i.e., these charts solve Equations 5 and 6 graphically for the optimal cratering case. In the analysis of TNT data and the preparation of Figures 5-13, the following criteria were used:

- a. The metric (SI) system of units was used, i.e., linear dimensions are expressed in metres, volumes in cubic metres, and charge weights in kilograms.
- b. Data from different sites were grouped together if they represented similar media following the classification presented in Part I.

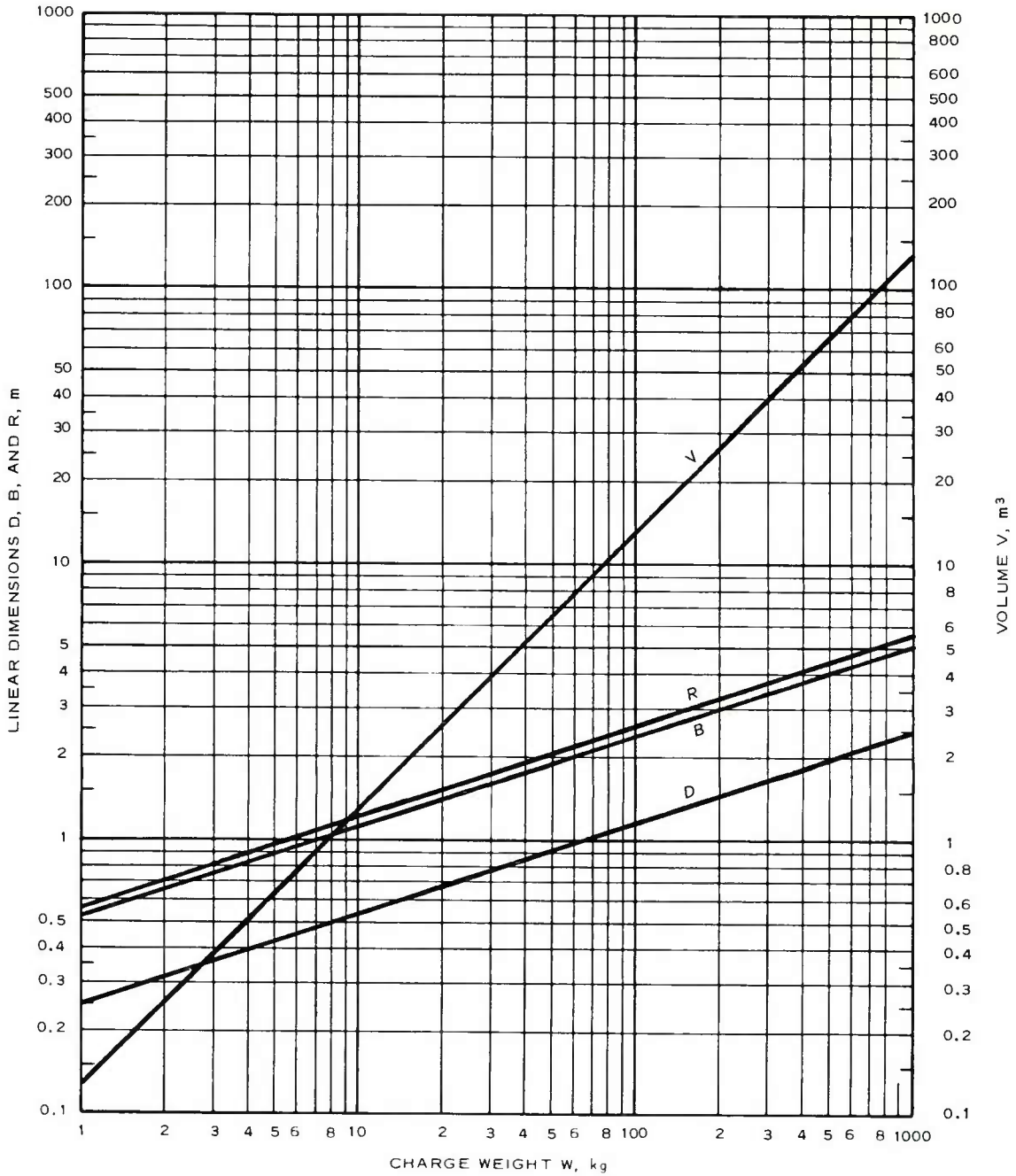


EQUATIONS

|                      |                     |
|----------------------|---------------------|
| OPTIMUM BURIAL DEPTH | $B = 0.52w^{1/3.0}$ |
| APPARENT RADIUS      | $R = 0.56w^{1/3.0}$ |
| APPARENT DEPTH       | $D = 0.25w^{1/3.0}$ |
| APPARENT VOLUME      | $V = 0.13w$         |

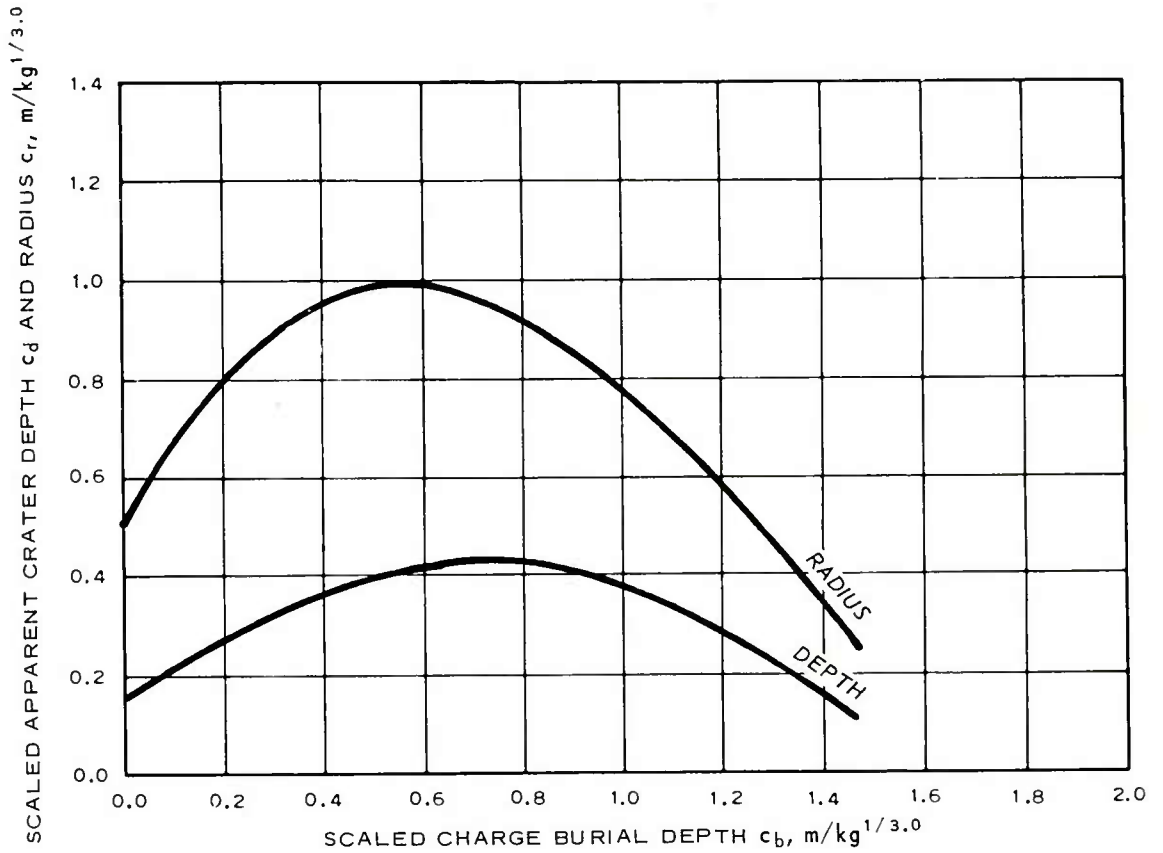
a. Scaled dimension curves

Figure 5. Scaled dimension curves and design chart for basalt, a high-strength rock (sheet 1 of 2)



b. Design chart

Figure 5 (sheet 2 of 2)

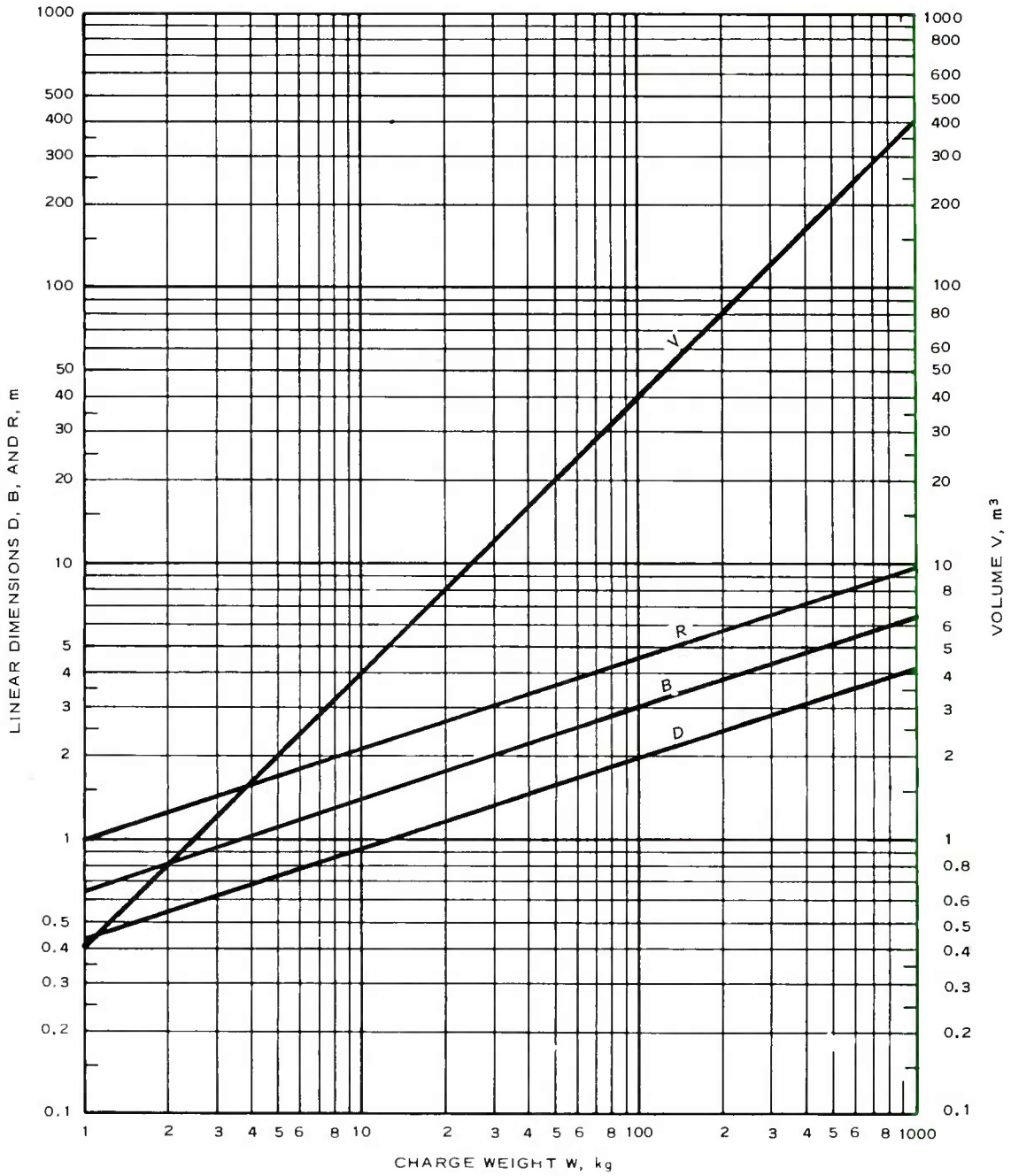


EQUATIONS

|                      |                     |
|----------------------|---------------------|
| OPTIMUM BURIAL DEPTH | $B = 0.65w^{1/3.0}$ |
| APPARENT RADIUS      | $R = 0.97w^{1/3.0}$ |
| APPARENT DEPTH       | $D = 0.42w^{1/3.0}$ |
| APPARENT VOLUME      | $V = 0.40w$         |

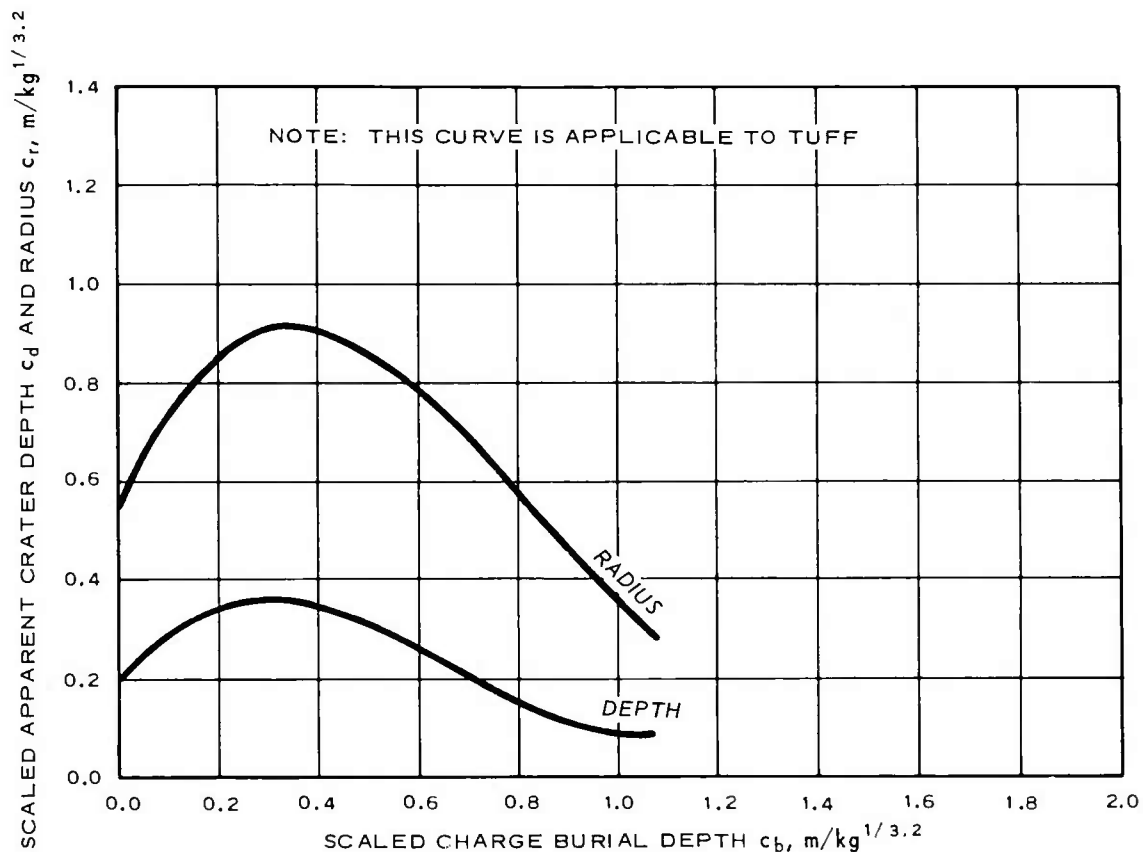
a. Scaled dimension curves

Figure 6. Scaled dimension curves and design chart for granite, a high-strength rock (sheet 1 of 2)



b. Design chart

Figure 6 (sheet 2 of 2)

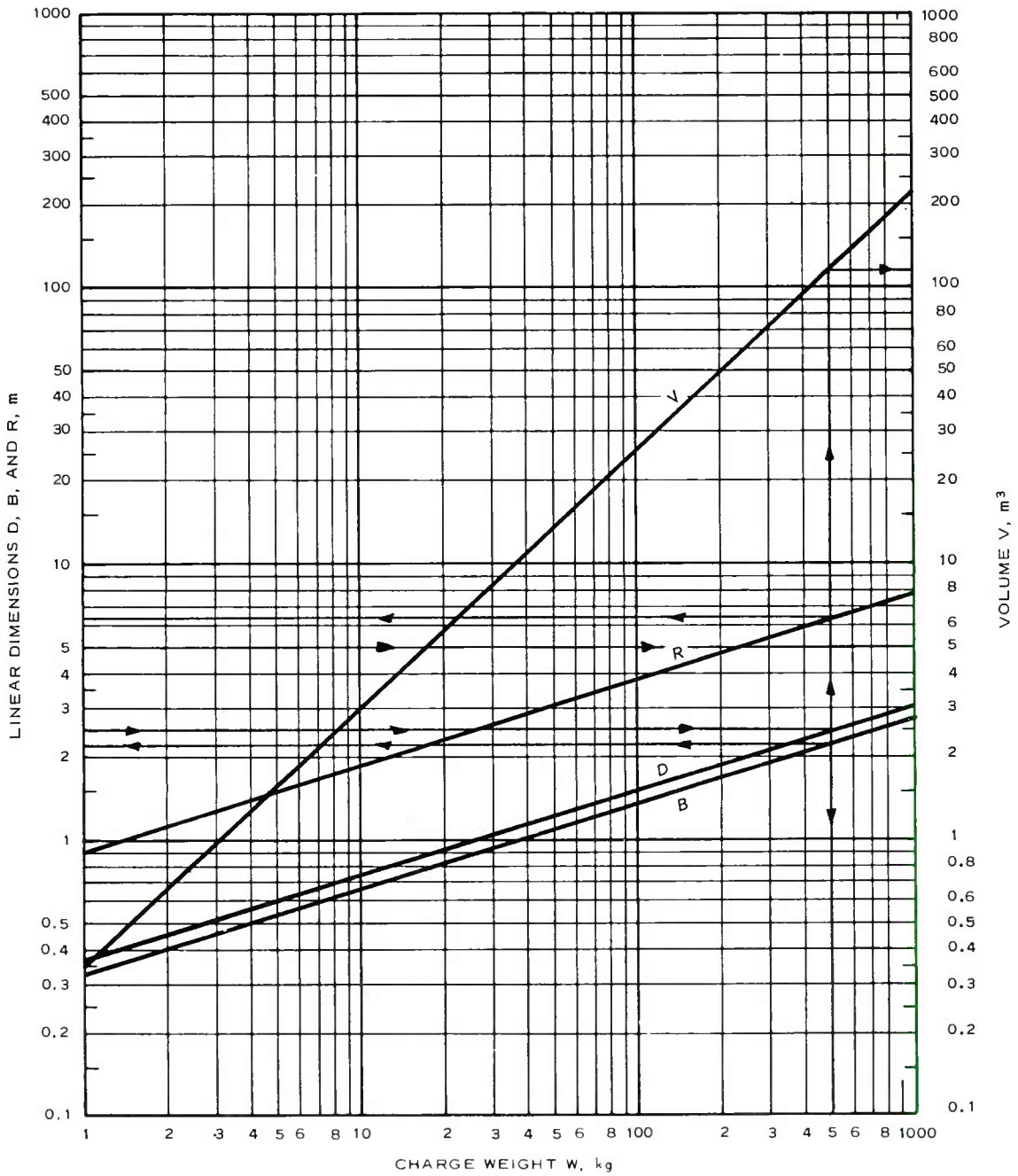


EQUATIONS

|                      |                     |
|----------------------|---------------------|
| OPTIMUM BURIAL DEPTH | $B = 0.32w^{1/3.2}$ |
| APPARENT RADIUS      | $R = 0.91w^{1/3.2}$ |
| APPARENT DEPTH       | $D = 0.36w^{1/3.2}$ |
| APPARENT VOLUME      | $V = 0.34w^{3/3.2}$ |

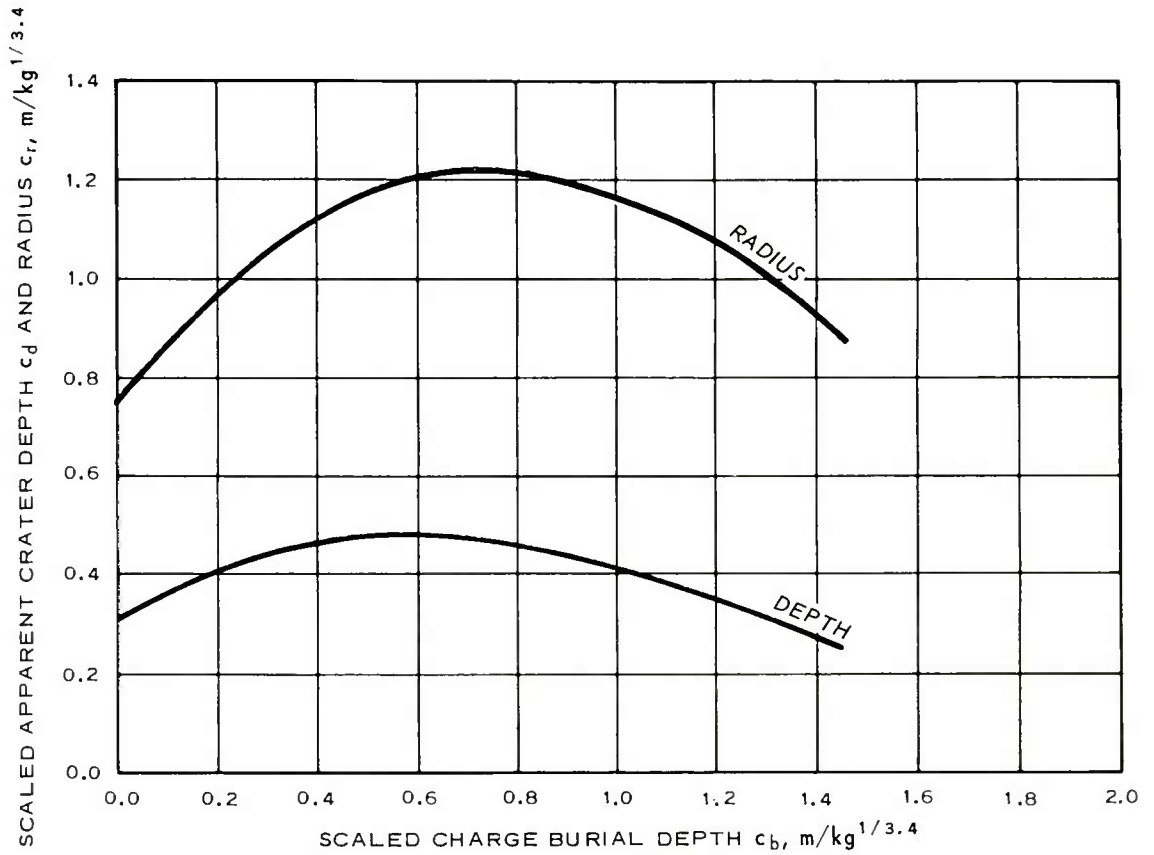
a. Scaled dimension curves

Figure 7. Scaled dimension curves and design chart for sandstone, an intermediate-strength rock (sheet 1 of 2)



b. Design chart

Figure 7 (sheet 2 of 2)

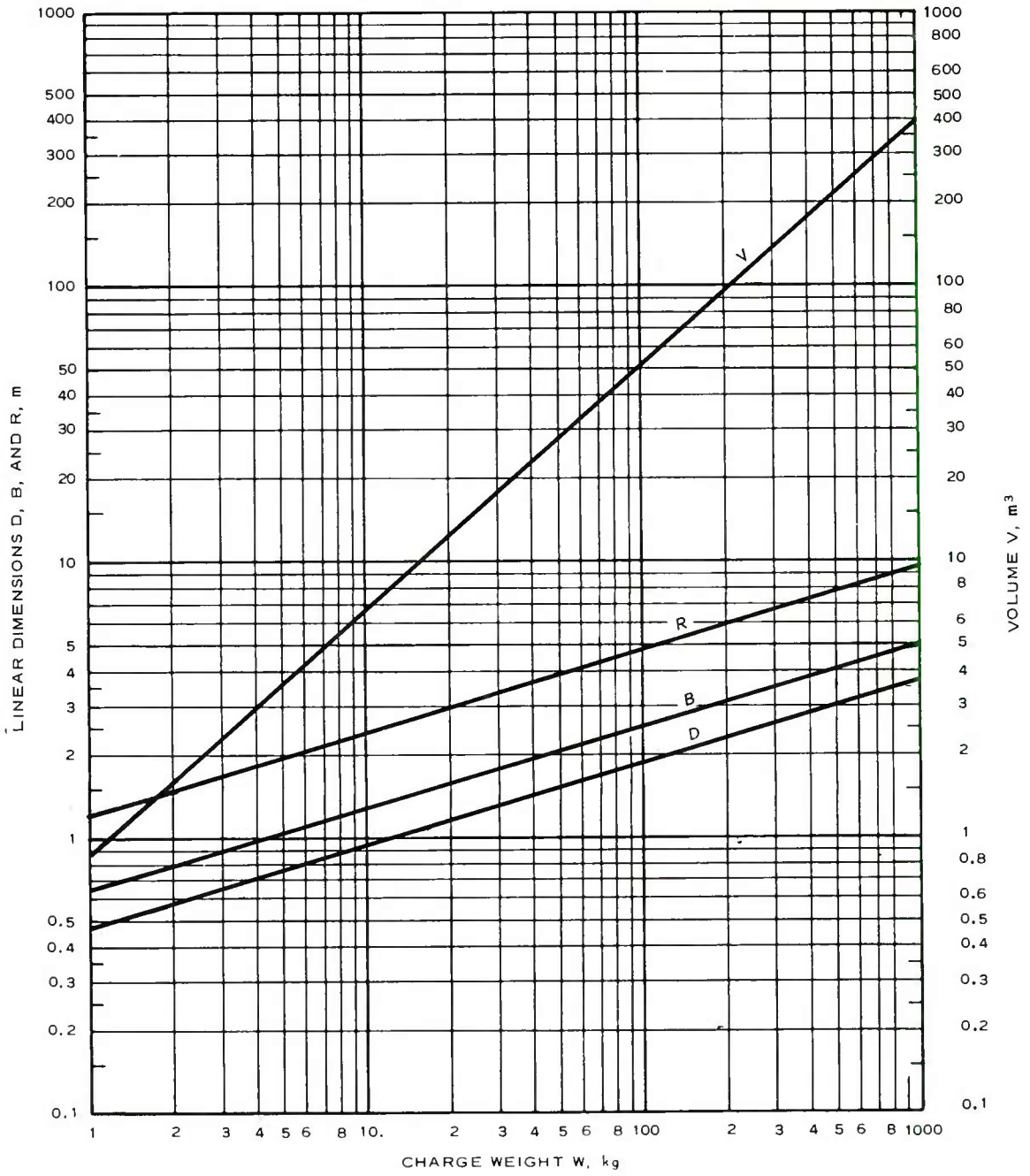


EQUATIONS

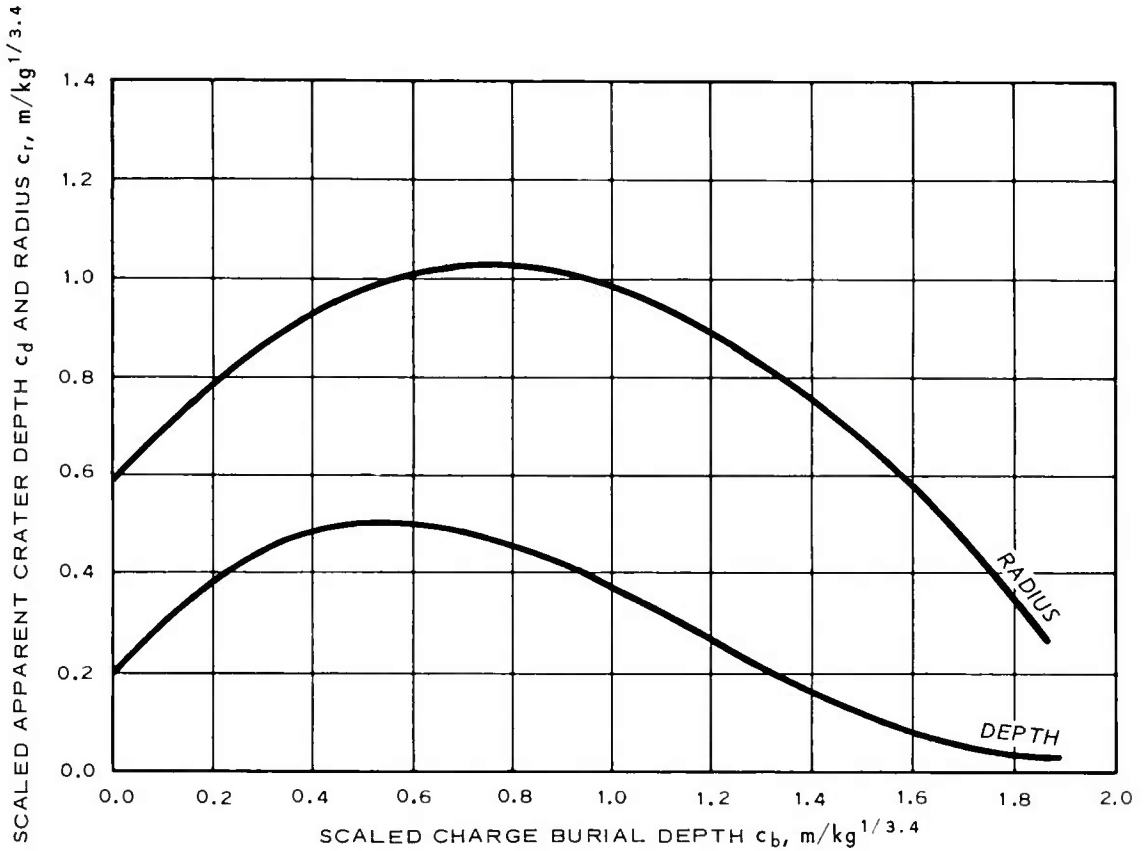
|                      |                     |
|----------------------|---------------------|
| OPTIMUM BURIAL DEPTH | $B = 0.66w^{1/3.4}$ |
| APPARENT RADIUS      | $R = 1.22w^{1/3.4}$ |
| APPARENT DEPTH       | $D = 0.48w^{1/3.4}$ |
| APPARENT VOLUME      | $V = 0.89w^{3/3.4}$ |

a. Scaled dimension curves

Figure 8. Scaled dimension curves and design chart for weak sandstones and shales, weak rocks (sheet 1 of 2)



b. Design chart  
 Figure 8 (sheet 2 of 2)

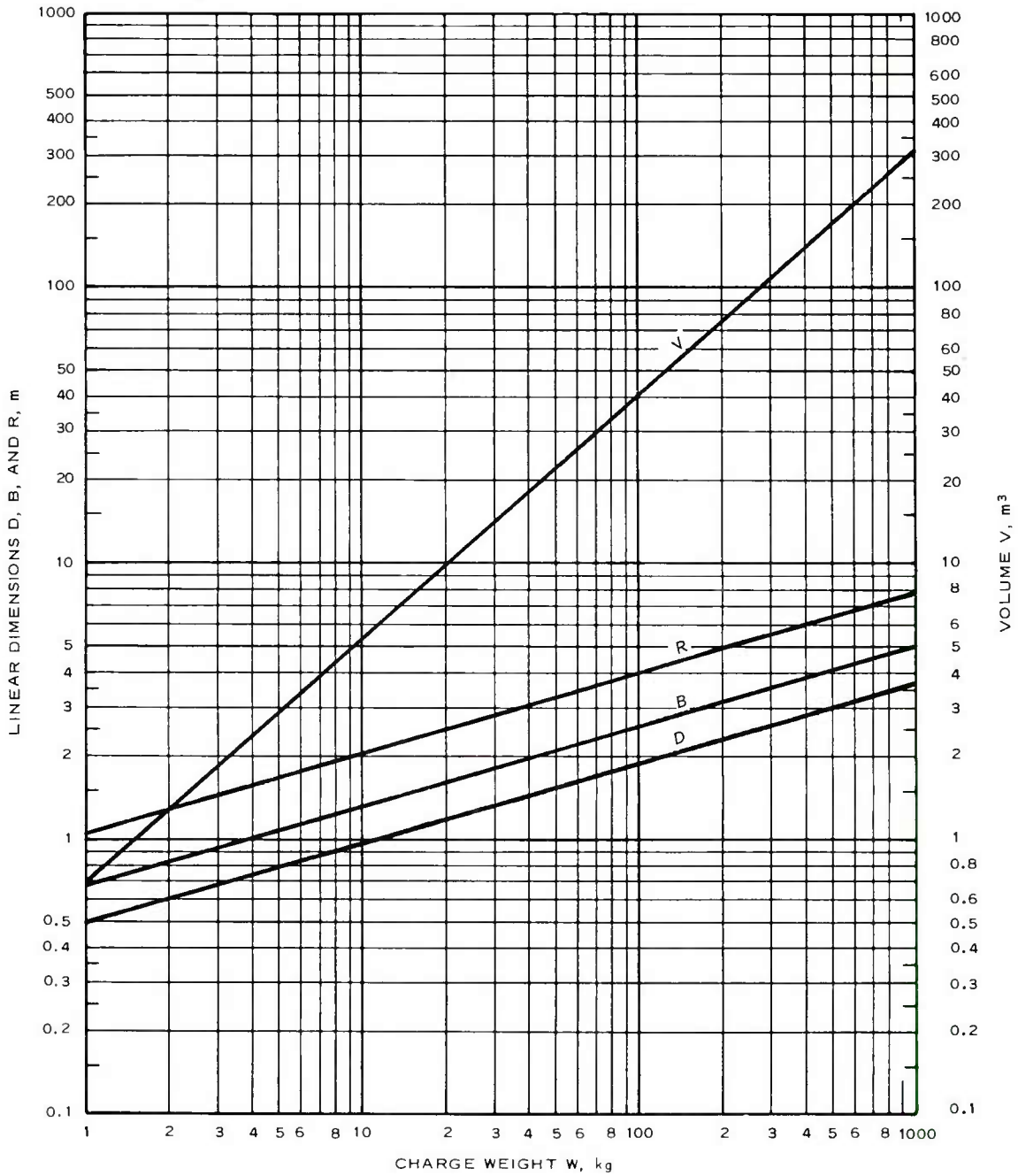


EQUATIONS

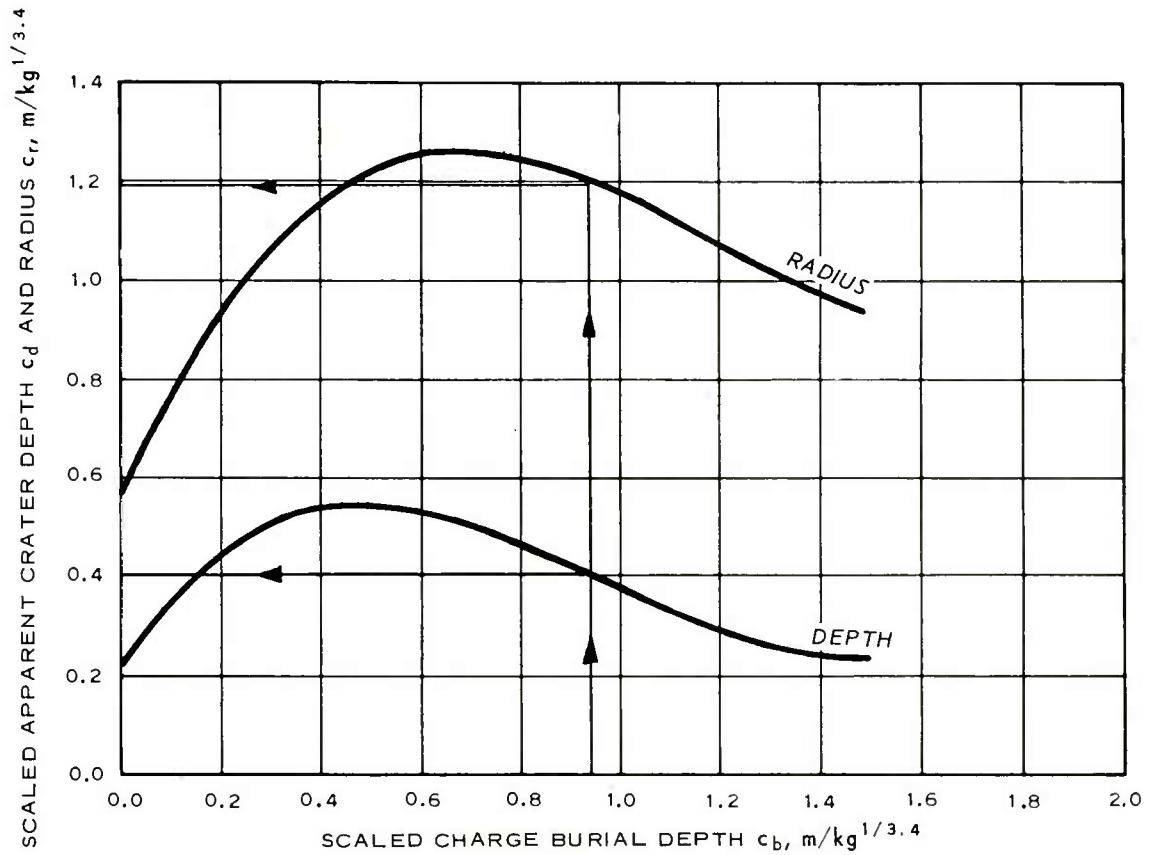
|                      |                     |
|----------------------|---------------------|
| OPTIMUM BURIAL DEPTH | $B = 0.66w^{1/3.4}$ |
| APPARENT RADIUS      | $R = 1.02w^{1/3.4}$ |
| APPARENT DEPTH       | $D = 0.49w^{1/3.4}$ |
| APPARENT VOLUME      | $V = 0.69w^{3/3.4}$ |

a. Scaled dimension curves

Figure 9. Scaled dimension curves and design chart for dry gravelly sand, a coarse-grained soil (GW) (sheet 1 of 2)



b. Design chart  
 Figure 9 (sheet 2 of 2)

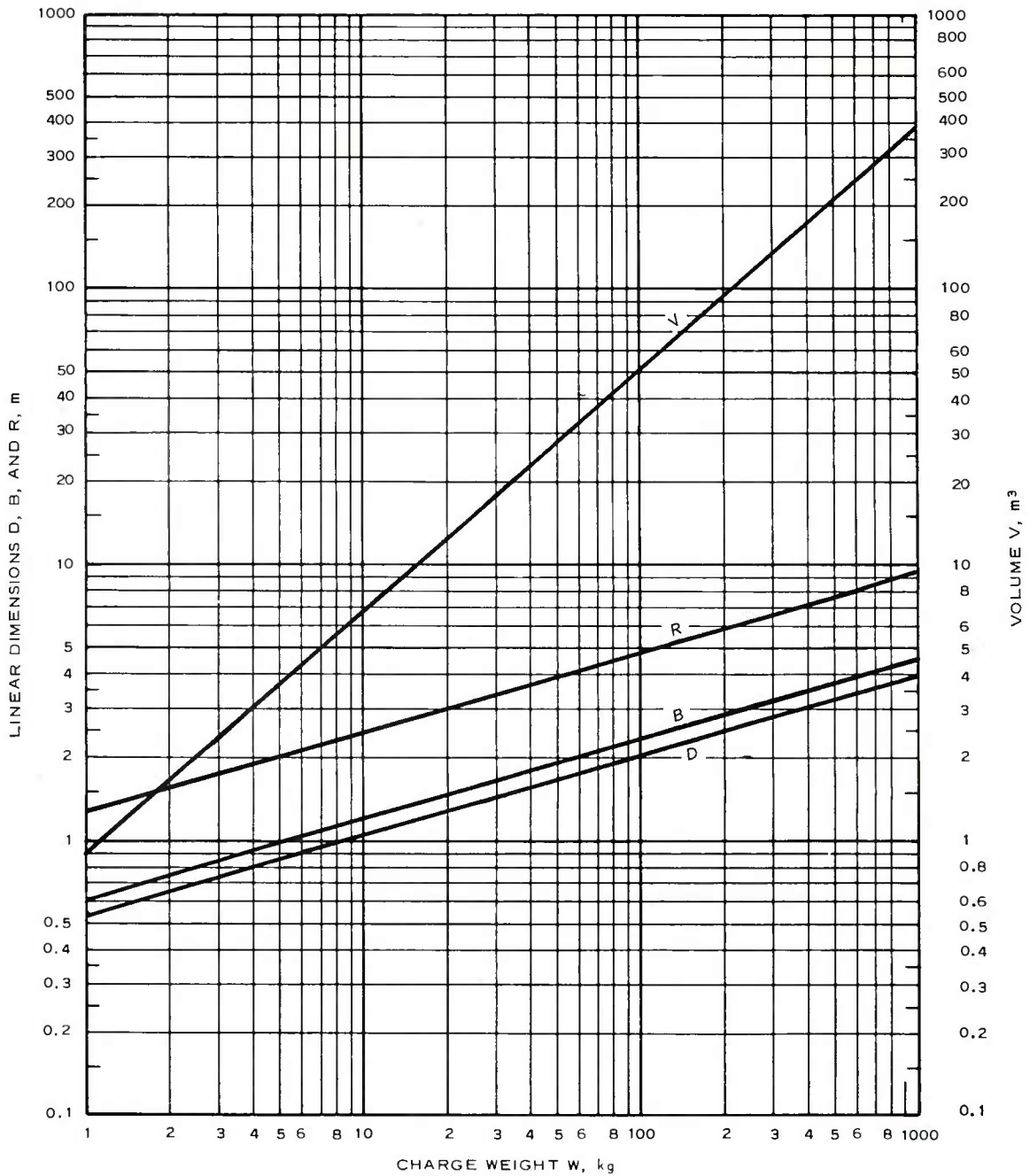


EQUATIONS

|                      |                     |
|----------------------|---------------------|
| OPTIMUM BURIAL DEPTH | $B = 0.60w^{1/3.4}$ |
| APPARENT RADIUS      | $R = 1.25w^{1/3.4}$ |
| APPARENT DEPTH       | $D = 0.53w^{1/3.4}$ |
| APPARENT VOLUME      | $V = 0.89w^{3/3.4}$ |

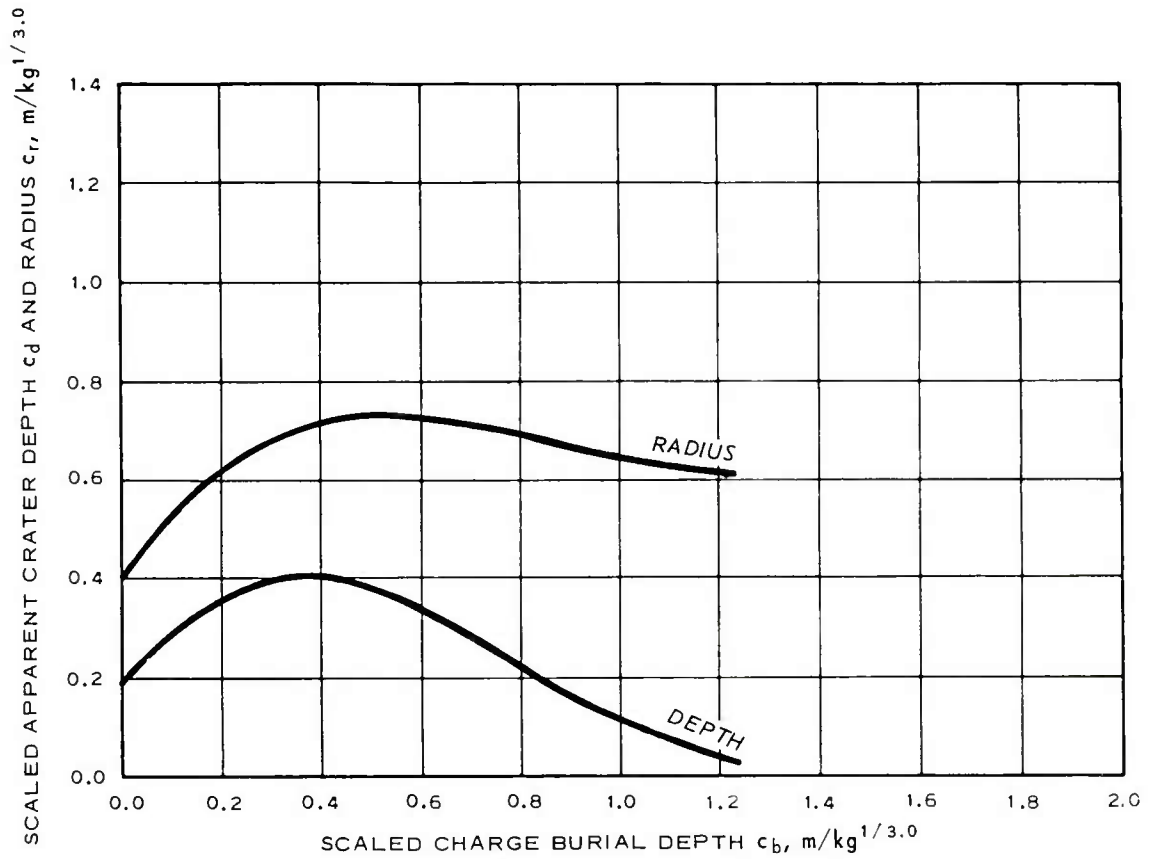
a. Scaled dimension curves

Figure 10. Scaled dimension curves and design chart for dry sand, a coarse-grained soil (sheet 1 of 2)



b. Design chart

Figure 10 (sheet 2 of 2)

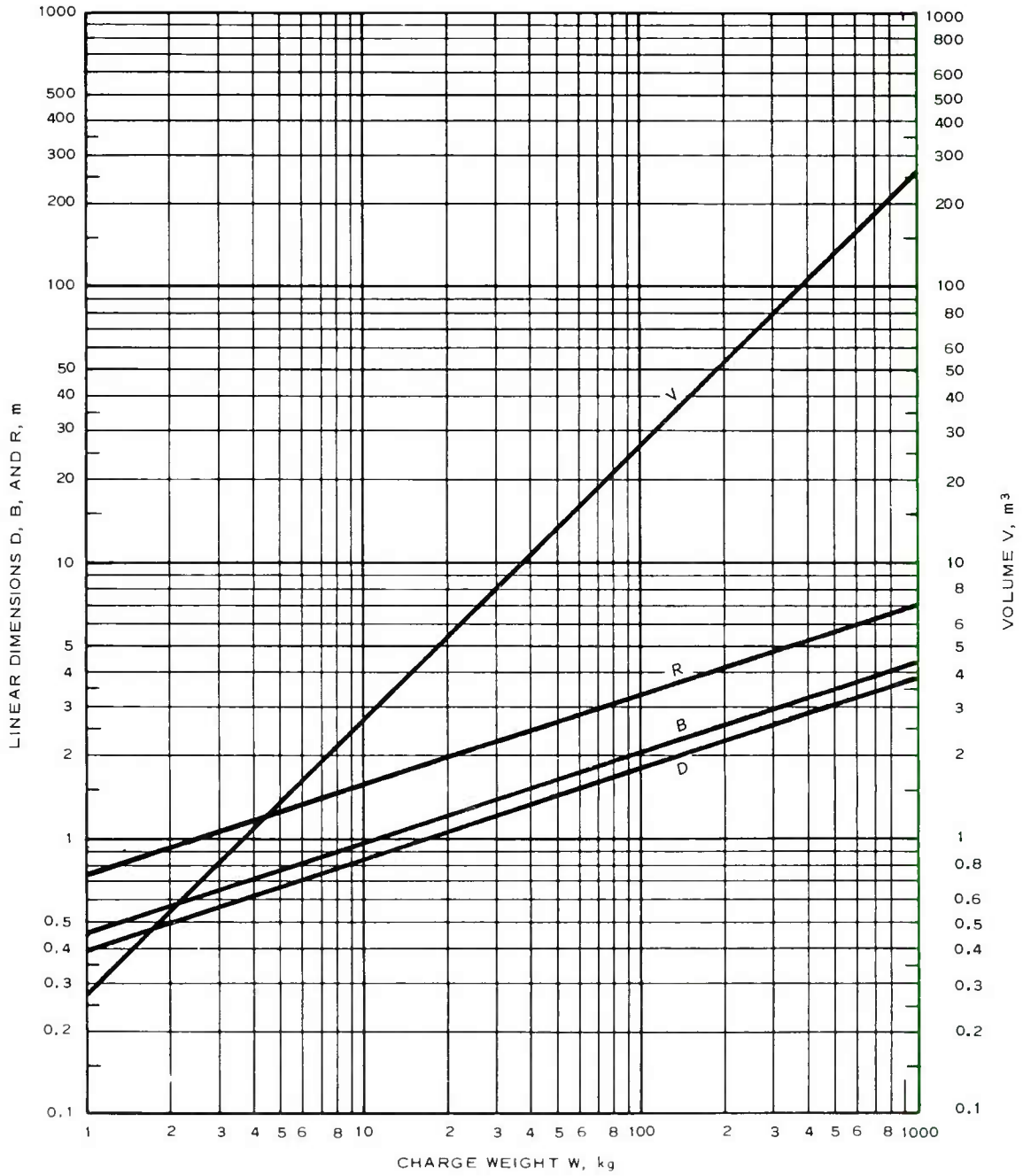


EQUATIONS

|                      |                     |
|----------------------|---------------------|
| OPTIMUM BURIAL DEPTH | $B = 0.45w^{1/3.0}$ |
| APPARENT RADIUS      | $R = 0.73w^{1/3.0}$ |
| APPARENT DEPTH       | $D = 0.39w^{1/3.0}$ |
| APPARENT VOLUME      | $V = 0.27w$         |

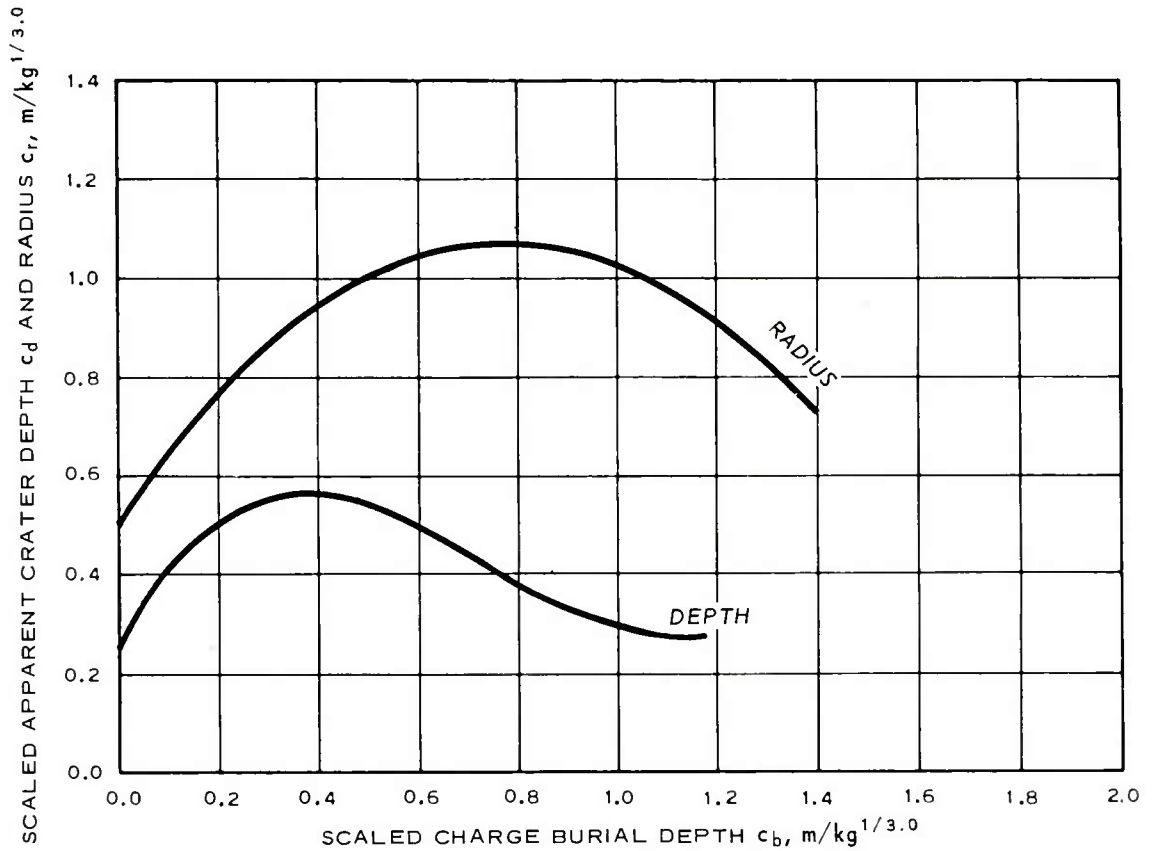
a. Scaled dimension curves

Figure 11. Scaled dimension curves and design chart for dry sandy clay, a coarse-grained soil (SC) (sheet 1 of 2)



b. Design chart

Figure 11 (sheet 2 of 2)

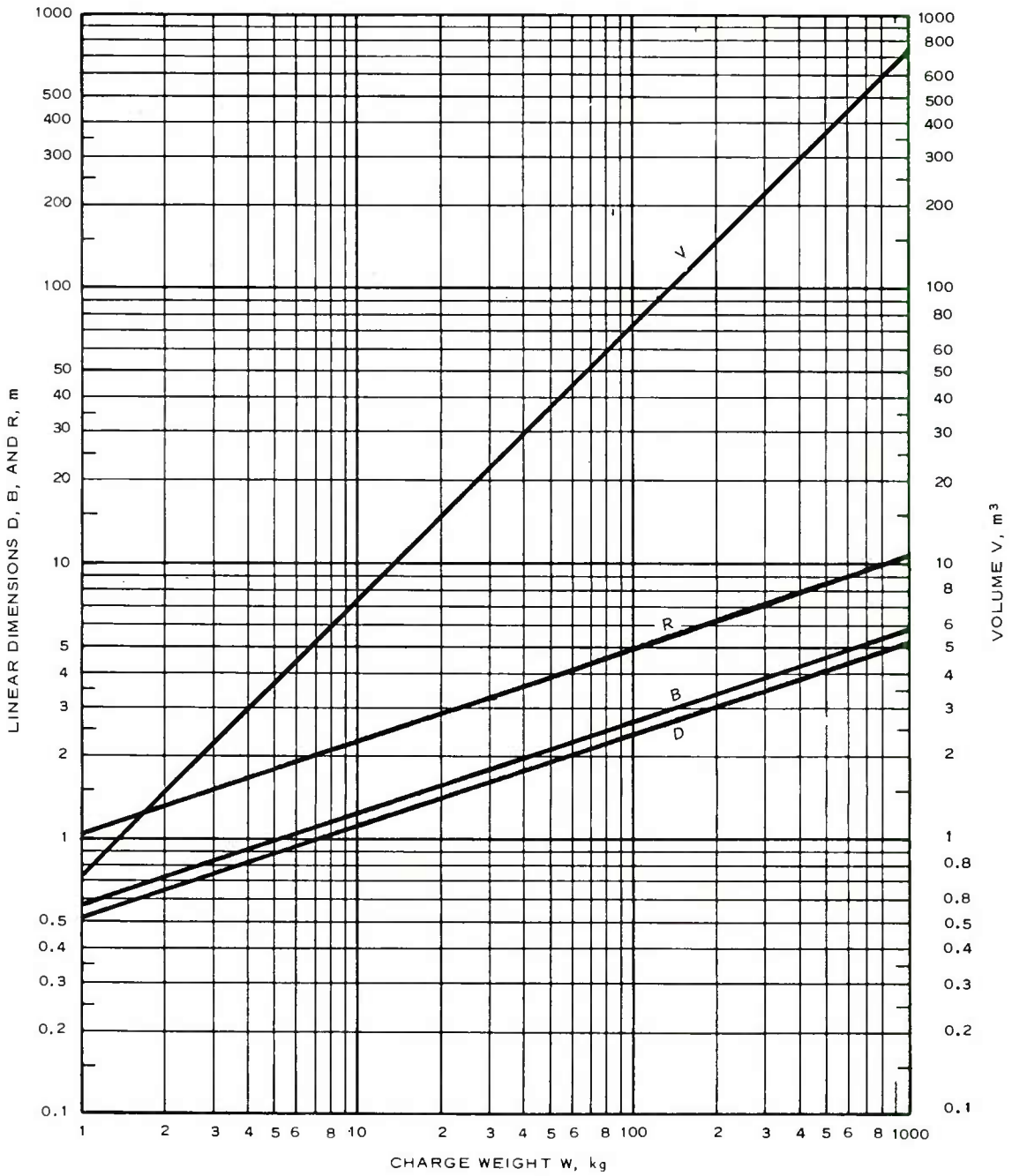


EQUATIONS

|                      |                     |
|----------------------|---------------------|
| OPTIMUM BURIAL DEPTH | $B = 0.57w^{1/3.0}$ |
| APPARENT RADIUS      | $R = 1.03w^{1/3.0}$ |
| APPARENT DEPTH       | $D = 0.51w^{1/3.0}$ |
| APPARENT VOLUME      | $V = 0.72w$         |

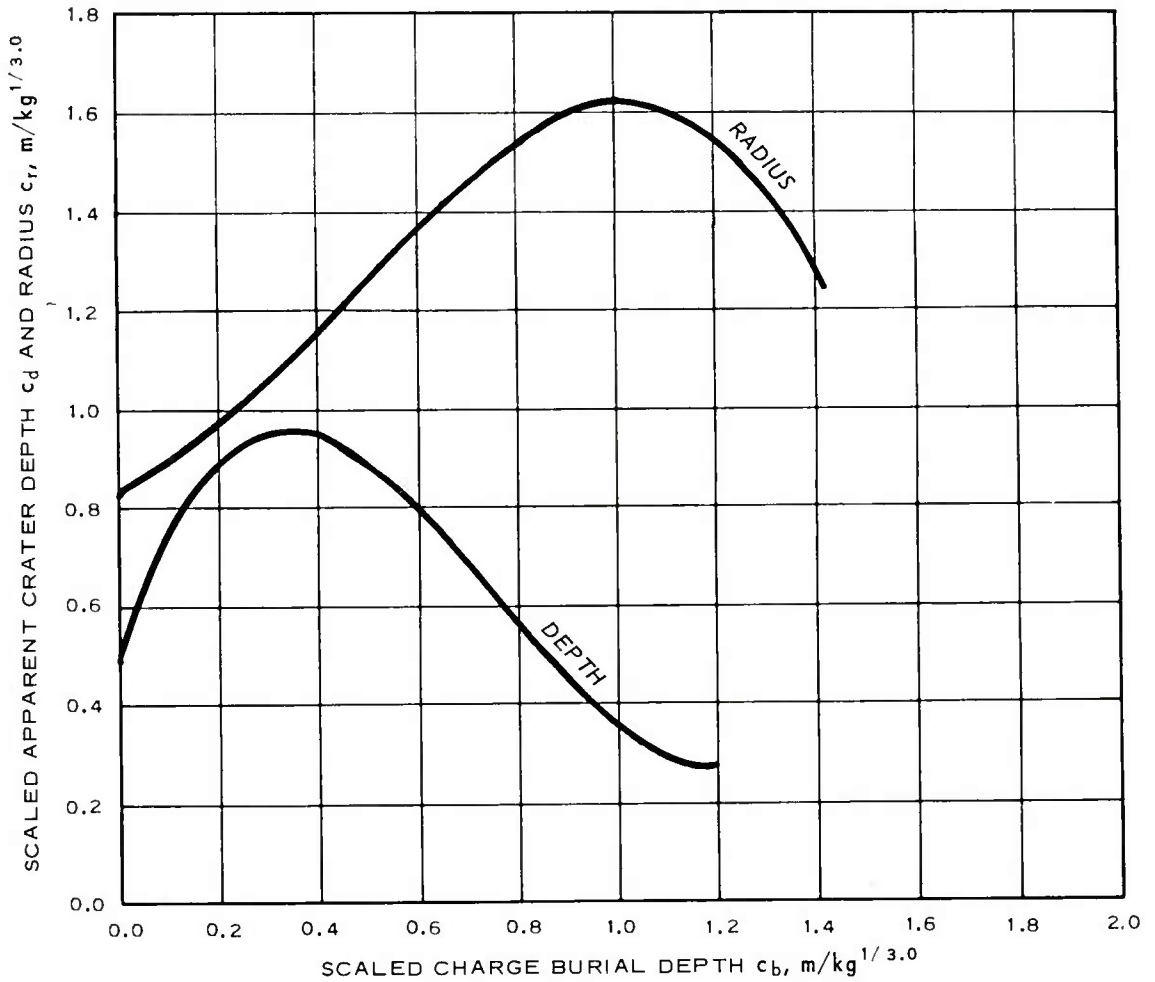
a. Scaled dimension curves

Figure 12. Scaled dimension curves and design chart for wet clay, a fine-grained soil (OH and MH) (sheet 1 of 2)



b. Design chart

Figure 12 (sheet 2 of 2)

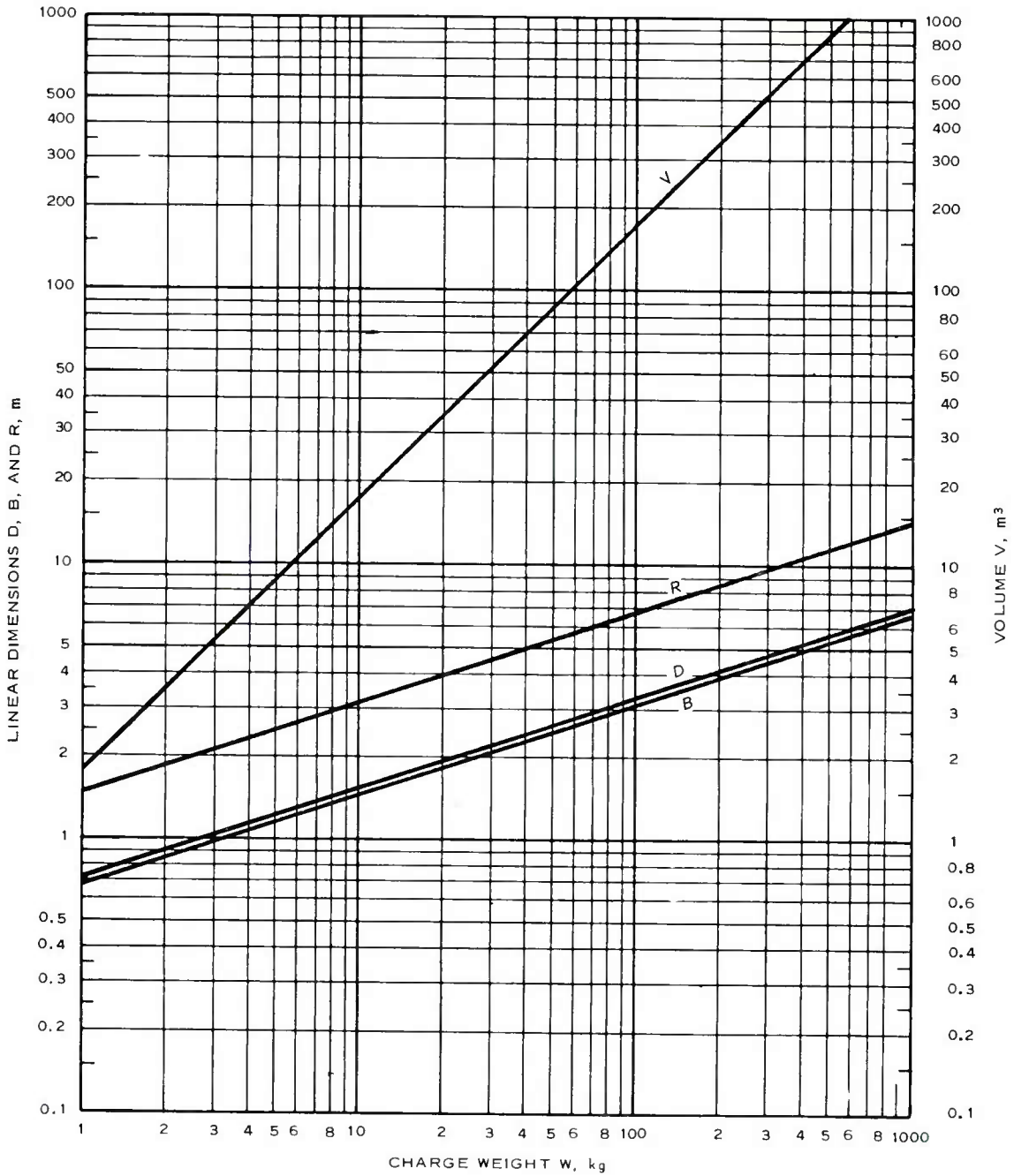


EQUATIONS

|                      |                     |
|----------------------|---------------------|
| OPTIMUM BURIAL DEPTH | $B = 0.68w^{1/3.0}$ |
| APPARENT RADIUS      | $R = 1.45w^{1/3.0}$ |
| APPARENT DEPTH       | $D = 0.71w^{1/3.0}$ |
| APPARENT VOLUME      | $V = 1.77w$         |

a. Scaled dimension curves

Figure 13. Scaled dimension curves and design for saturated silty clay, a fine-grained soil (sheet 1 of 2)



b. Design chart

Figure 13 (sheet 2 of 2)

- c. The third-order polynomial fit was chosen to represent the scaled dimension curves.
- d. The least-squares method was used to fit the curves.
- e. The value of  $a$  was assumed to be 3.0, 3.1, 3.2...3.6 for each medium, and that value that presented the smallest scatter between data point plots for all charge weights was chosen as the representative value for the considered medium.
- f. In the preparation of the design charts, the optimum burial depth for each medium was considered to be the average of the optimum burial depths for crater radius and depth as determined from the peaks of the curves on the corresponding scaled dimension plot.
- g. Scaled radius and scaled depth curves are presented in the same chart.
- h. Only the parameter obtained from the scaled volume curve is presented, not the curve.

15. Table 3 summarizes the results obtained from the scaled dimension plots, and gives additional information regarding the data base used for the analysis of each medium. Necessary charge weights and burial depths and predicted crater dimensions may be calculated for the optimal cratering case in the various media by substitution of the values of appropriate exponents and coefficients from Table 3 into Equations 5 and 6.

### Single-Crater Design Examples

#### Example 1

16. Problem. To predict the apparent crater radius and depth to be expected from the detonation of a single charge of 500 kg\* of TNT at 6-m burial depth in dry sand.

17. Solution. The following parameters are given:

---

\* A table of factors for converting metric (SI) units of measurement to U. S. customary units and U. S. customary units to metric (SI) units is given on page 3.

$$w = 500 \text{ kg}$$

$$B = 6.0 \text{ m}$$

$$a = 3.4 \text{ (Table 3)}$$

Using Equation 7, the scaled burial depth may be calculated:

$$c_b = \frac{B}{w^{1/a}} = \frac{6.0}{500^{1/3.4}} = 0.96$$

Entering the scaled dimension curve for dry sand (Figure 10a) with  $c_b = 0.96$  gives the corresponding values of  $c_r$  and  $c_d$

$$c_r = 1.19 \text{ m/kg}^{1/3.4} \quad \text{and} \quad c_d = 0.40 \text{ m/kg}^{1/3.4}$$

By Equation 5:

$$R = c_r w^{1/a} = 1.19 \times 500^{1/3.4} = 7.4 \text{ m}$$

$$D = c_d w^{1/a} = 0.40 \times 500^{1/3.4} = 2.5 \text{ m}$$

The resulting single crater will have a 7.4-m apparent radius and a 2.5-m apparent depth.

#### Example 2

18. Problem. To determine the single-charge weight of TNT and charge burial depth necessary to excavate a crater with an apparent radius of at least 5 m and an apparent depth of at least 2.5 m in sandstone.

19. Solution. The following parameters are given:

$$R \geq 5.0 \text{ m}$$

$$D \geq 2.5 \text{ m}$$

This problem can be solved using either mathematical procedures or the charts in Figures 5-13.

a. Mathematical.

From Table 3:

$$a = 3.2$$

$$c_b = 0.32$$

$$c_r = 0.91$$

$$c_d = 0.36$$

$$c_v = 0.34$$

From Equation 5a:

$$w = \left( \frac{R}{c_r} \right)^a = \left( \frac{5.0}{0.91} \right)^{3.2} = 233.22 \text{ kg}$$

$$w = \left( \frac{D}{c_d} \right)^a = \left( \frac{2.5}{0.36} \right)^{3.2} = 493.45 \text{ kg}$$

These calculations show that a charge of at least 493.45 kg of TNT will be necessary to achieve the required apparent depth of 2.5 m and that the required apparent radius of 5.0 m could be achieved with a 233.22-kg charge. To determine the apparent radius that will be obtained using 493.45 kg of TNT, use Equation 5:

$$R = c_r w^{1/a} = (0.91)(493.45)^{1/3.2} = 6.32 \text{ m}$$

Also from Equation 5, the required charge burial depth is

$$B = c_b w^{1/a} = (0.32)(493.45)^{1/3.2} = 2.22 \text{ m}$$

Using Equation 6, the apparent crater volume is

$$V = c_v w^{3/a} = (0.34)(493.45)^{3/3.2} = 113.87 \text{ m}^3$$

b. Graphic. Enter Figure 7b at  $R = 5.0$  and read 233 kg on curve R. Enter Figure 7b at  $D = 2.5$  and read +495 kg on curve D. The value +495 from curve D is larger than the value 233 from curve R; therefore, a

charge weight of 495 kg must be used. Read values of R , B , and V from the appropriate curves for a charge weight of 495 kg:

$$R = 6.3 \text{ m}$$

$$B = 2.2 \text{ m}$$

$$V = 113 \text{ m}^3$$

### PART III: DITCHING DESIGNS

20. This part develops criteria for the design of ditches based upon the single-crater empirical scaling relationships discussed in Part II. The experimental data base for high-explosive ditching (Appendix C) is not as extensive as that for single craters, and is largely limited to row shots in soils. Thus, conclusions regarding row-crater effects are based largely upon a small number of simultaneously detonated high-explosive tests in soils.

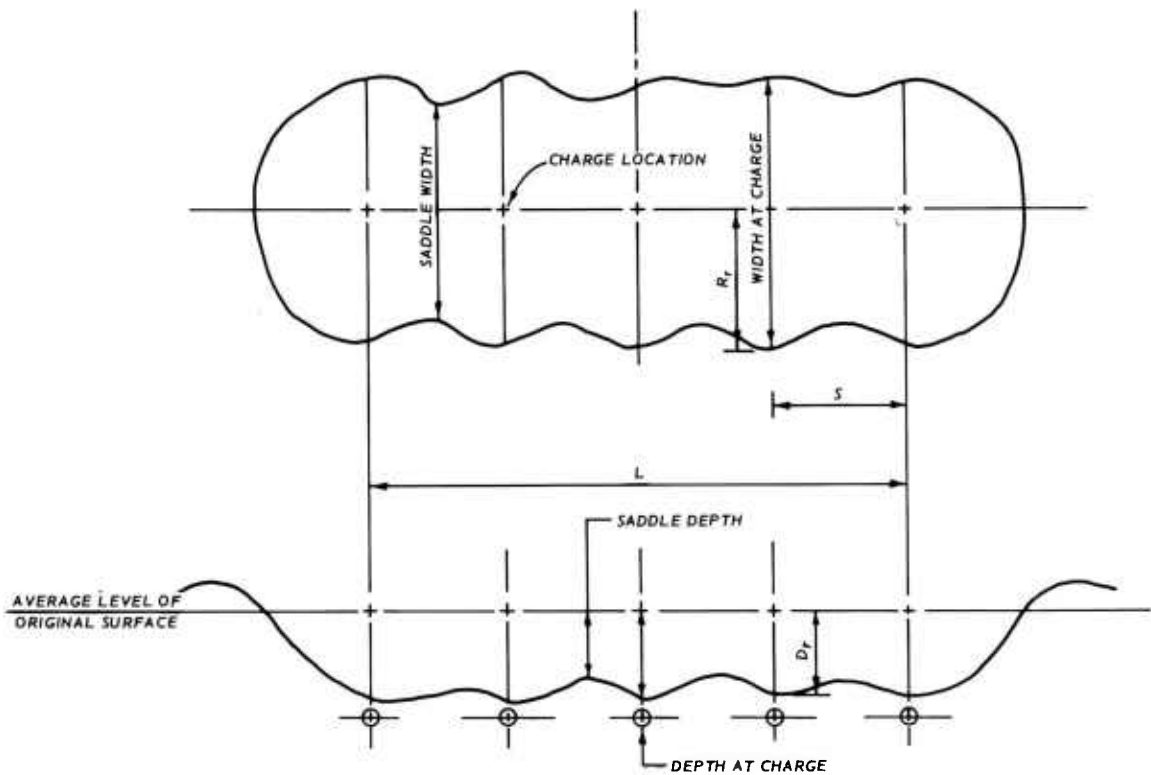
#### Ditch Smoothness

21. Criteria for ditch smoothness have been experimentally developed from row cratering in dry sandy clay.<sup>25</sup> Figure 14 shows a typical row crater with associated nomenclature and notation. It is apparent from this figure that ditch width and depth may vary, with the largest dimensions occurring close to the individual charge locations and the smallest dimensions occurring at "saddles" midway between the individual charge locations. If the spacing between charges  $S$  is sufficiently small, saddle dimensions will be approximately as large as near-charge dimensions, and a smooth ditch will be produced. However, it is also true that  $S$  must not be reduced any more than is necessary to obtain a smooth ditch, since production times and costs would be unnecessarily increased by closer-than-necessary spacings.

22. Figure 15 is a reprint of Figure 11 with experimentally developed row crater smoothness information superimposed. The curve labeled "Spacing Between Row Charges" represents  $c_s$ , the scaled upper limit for  $S$  where:

$$\frac{\text{Saddle width}}{\text{Width at charge}} \geq 0.95$$

$$\frac{\text{Saddle depth}}{\text{Depth at charge}} \geq 0.95$$



$$L = S(n-1) \quad (11)$$

NOTE:  $R_r$  = AVERAGE APPARENT HALF-WIDTH OF ROW CRATER AT CHARGE LOCATIONS  
 $D_r$  = MAXIMUM APPARENT DEPTH OF ROW CRATER  
 $L$  = DITCH LENGTH FROM FIRST TO LAST CHARGE LOCATION  
 $n$  = NUMBER OF CHARGES IN ROW

Figure 14. Plan and profile views of a five-charge row crater ( $n = 5$ )

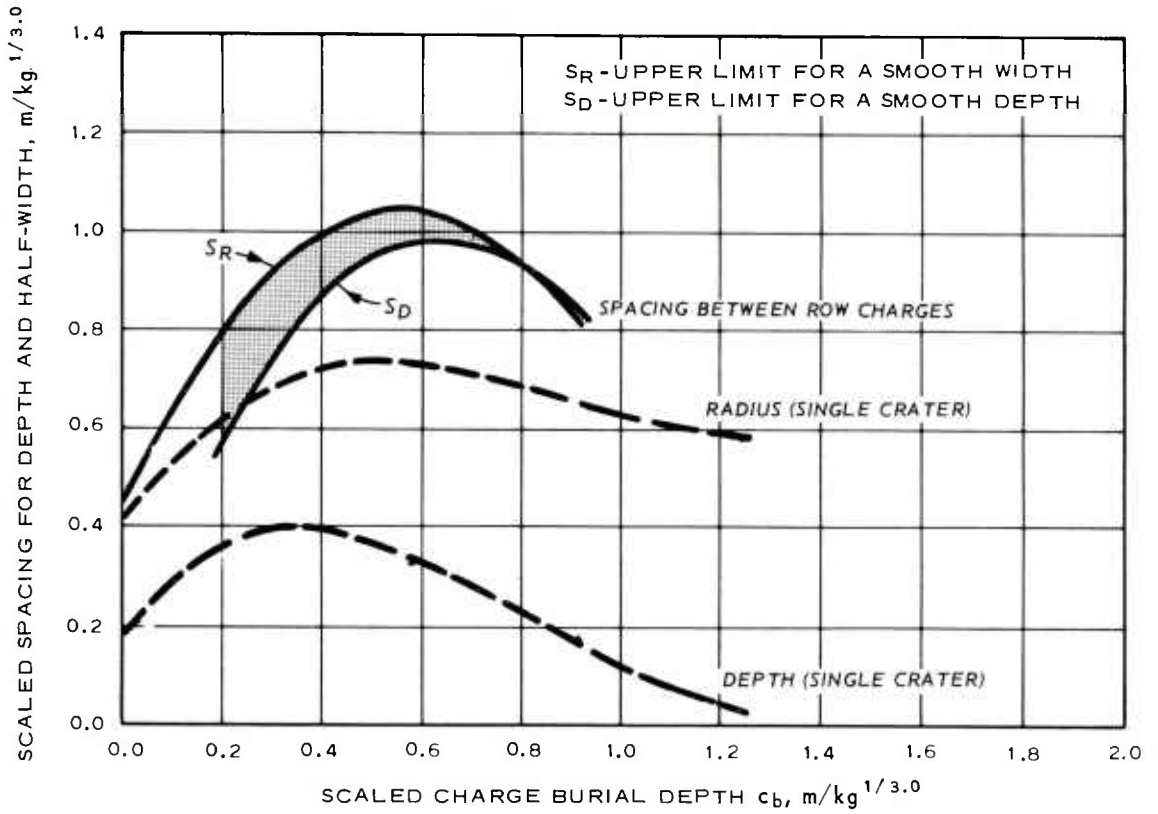


Figure 15. Scaled dimension curves for single and row craters for dry sandy clay, a coarse-grained soil (SC)

In other words, spacings  $S$  that correspond to values under this curve will yield smooth ditches, i.e., ditches within which widths and depths at the saddles are at least 95 percent as large as those at the charge locations. The shaded area just above this curve is a zone within which the ditches produced will maintain saddle widths of at least 95 percent of widths at charges, but which may have saddle depths as small as 60 percent of depths at charges.

23. From Table 3, scaled optimum burial depth  $c_b$  for dry sandy clay is 0.45. The ratio of the values of the scaled spacing between row charges  $c_s$  and the scaled apparent radius  $c_r$  at abscissa value  $c_b = 0.45$  will give the spacing between row charges  $S$  in terms of the apparent radius  $R$  expected from a single charge emplaced at optimum burial depth in dry sandy clay:

$$\frac{S}{R} = \frac{c_s}{c_r} = \frac{0.90}{0.72} = 1.25$$

or

$$S = 1.25R \quad (12)$$

In the absence of comprehensive experimental data from other media, it is assumed that a smooth row crater from charges buried at optimum burial depth in any soil will require a spacing between row charges  $S$  of 1.25 times the apparent crater radius  $R$  that would be expected from a single charge emplaced at optimum burial depth for that medium. In actual practice with a variety of explosives in a variety of media, this relationship works well.

#### Ditching Design Example

24. Problem. A drainage ditch is to be excavated in wet clay on flat terrain. A minimum width of 8.0 m and a minimum depth of 1.5 m are required. Ditch length is to be 2000 m. Determine the amount of TNT required to produce the ditch with a single row of charges, and give the

charge size, burial depth, and spacing between charges to produce the ditch.

Given:

$$\text{Required ditch width } 2R_r \geq 8.0 \text{ m}$$

$$\text{Required ditch depth } D_r \geq 1.5 \text{ m}$$

$$\text{Required ditch length } L = 2000 \text{ m}$$

From Table 3:

$$a = 3.0$$

$$c_b = 0.57$$

$$c_r = 1.03$$

$$c_d = 0.51$$

The corresponding single crater will have:

$$R = R_r = 4.0 \text{ m}$$

$$D = D_r = 1.5 \text{ m}$$

Using Equation 5a the single charge may be calculated:

$$w = \left( \frac{R}{c_r} \right)^a = \left( \frac{4.0}{1.03} \right)^{3.0} = 58.57 \text{ kg}$$

and

$$w = \left( \frac{D}{c_d} \right)^a = \left( \frac{1.5}{0.51} \right)^{3.0} = 25.44 \text{ kg}$$

A charge of at least 58.57 kg of TNT will be necessary for each individual charge in the row shot to achieve the required ditch width  $2R_r = 8.0$  m (the required ditch depth  $D_r$  could be achieved with 25.44-kg charges). To determine the apparent depth that will actually be achieved using 58.57 kg of TNT, use Equation 5:

$$D = c_d w^{1/a} = 0.51 \times 58.57^{1/3.0} = 1.98 \text{ m}$$

Also from Equation 5, required charge burial depth may be calculated:

$$B = c_b w^{1/a} = 0.57 \times 58.57^{1/3.0} = 2.21 \text{ m}$$

Spacing between charges (from paragraph 23):

$$S = 1.25R = 1.25 \times 4.00 = 5.00 \text{ m}$$

The length of this ditch will have a uniform cross section and is equal to the distance between the first and last charges. Using Equation 11 (Figure 14), the number of charges  $n$  may be calculated.

$$L = S(n - 1)$$

$$n = \left(\frac{L}{S}\right) + 1 \frac{2000}{5} + 1 = 401$$

Four hundred and one 58.57-kg charges will be required to excavate this ditch, or a total of 23,487 kg of TNT. The individual charges should be emplaced 2.21 m deep and spaced 5.00 m apart in the row.

#### PART IV: CONCLUSIONS

25. The large majority of data in the TNT cratering and ditching data base are from tests in dry soils although rock test sites are well represented in the data base. The weakest area is that for wet and saturated soils. TNT cratering data for saturated sand, though available in the data base, were inadequate for the analyses of this study.

26. The data base for cratering with single buried TNT charges is the most comprehensive available for any single explosive. It provides the best available basis for the comparison of cratering effects in differing media, and the standard for use in determining the cratering effectiveness of other explosives.

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Table 1

Media Classification for Explosive Excavation (from Reference 4)

| <u>Classification</u> | <u>Description</u>   |
|-----------------------|--|
|                       | <u>Rock Type</u>   |
| Weak                  | Less than 27,580 kPa (4,000 psi) unconfined compressive strength   |
| Intermediate-strength | Between 27,580 and 110,320 kPa (16,000 psi) unconfined compressive strength  |
| High-strength         | Greater than 110,320 kPa unconfined compressive strength   |
|                       | <u>Degree of Saturation or Water Content for Soils</u>   |
| Dry                   | Less than 50 percent saturated or less than 10 percent water content for soil or less than 3 percent water content for rock            |
| Wet                   | Between 50 and 90 percent saturated or greater than 10 percent water content for soil or greater than 3 percent water content for rock |
| Saturated             | Greater than 90 percent  |

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Note: See Table 2 for a discussion of soil types.

Table 2

Summary of Unified Soil Classification System

(Adapted from Reference 6)

| Major Divisions      |                                      | Symbol | Soil Type  |
|----------------------|--------------------------------------|--------|--|
| Coarse-grained soils | Gravel and Gravelly soils            | GW     | Well-graded gravels or gravel-sand mixtures, little or no fines  |
|                      |                                      | GP     | Poorly graded gravels or gravel-sand mixtures, little or no fines  |
|                      |                                      | GM     | Silty gravels, gravel-sand-silt mixtures   |
|                      |                                      | GC     | Clayey gravels, gravel-sands-clay mixtures   |
|                      | Sand and Sandy soils                 | SW     | Well-graded sands or gravelly sands, little or no fines  |
|                      |                                      | SP     | Poorly graded sands or gravelly sands, little or no fines  |
|                      |                                      | SM     | Silty sands, sand-silt mixtures  |
|                      |                                      | SC     | Clayey sands, sand-silt mixtures   |
| Fine-grained soils   | Silts and Clays<br>Liquid limit < 50 | ML     | Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity |
|                      |                                      | CL     | Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays                  |
|                      |                                      | OL     | Organic silts and organic silt-clays of low plasticity   |
|                      | Silts and Clays<br>Liquid limit > 50 | MH     | Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts                                |
|                      |                                      | CH     | Inorganic clays or high plasticity, fat clays  |
|                      |                                      | OH     | Organic clays of medium to high plasticity, organic silts  |
| Highly organic soils |                                      | PT     | Peat and other highly organic soils  |

Note: Coarse-grained soils: Soils having 50 percent or less passing the No. 200 sieve. The coarse-grained soils include gravels, gravelly soils, sands, and sandy soils. The letter G is used to indicate a gravel, and the letter S is used to indicate sand. Gravel is material between 3 in. in diameter and the No. 4 (4.7 mm) sieve size, and sand is material between the No. 4 sieve size and the No. 200 (0.074 mm) sieve size. Particles larger than 3 in. in diameter are termed cobbles. Sand is divided into coarse, medium, and fine, the divisions being at the No. 10 and 40 sieve sizes.

Fine-grained soils: Soils having more than 50 percent passing the No. 200 sieve. The fine-grained soils are not divided according to grain size but according to plasticity and compressibility.

Table 3

## Cratering Parameters for Optimum Burial Depth

| Medium Name                | Coefficient ( $m/kg^{1/a}$ ) |       |       |       | No. of Craters Used | Charge |          | Source |                   |                   |
|----------------------------|------------------------------|-------|-------|-------|---------------------|--------|----------|--------|-------------------|-------------------|
|                            | a                            | $c_b$ | $c_r$ | $c_d$ |                     | $c_v$  | No. Used |        | Minimum Weight kg | Maximum Weight kg |
| Basalt                     | 3.0                          | 0.52  | 0.56  | 0.25  | 0.13                | 34     | 8        | 3.6    | 18,143.7          | 9-11              |
| Granite                    | 3.0                          | 0.65  | 0.97  | 0.42  | 0.40                | 11     | 2        | 145.1  | 1,161.2           | 12                |
| Sandstone                  | 3.2                          | 0.32  | 0.91  | 0.36  | 0.34                | 33     | 11       | 3.6    | 145,149.6         | 13-15             |
| Weak sandstones and shales | 3.4                          | 0.66  | 1.22  | 0.48  | 0.89                | 20     | 5        | 3.6    | 90.7              | 16                |
| Dry gravelly sand          | 3.4                          | 0.66  | 1.02  | 0.49  | 0.69                | 46     | 8        | 98.0   | 447,881.7         | 17-22             |
| Dry sand                   | 3.4                          | 0.60  | 1.25  | 0.53  | 0.89                | 13     | 3        | 145.2  | 18,143.7          | 23                |
| Dry sandy clay             | 3.0                          | 0.45  | 0.72  | 0.39  | 0.27                | 89     | 9        | 29.0   | 145,149.6         | 17, 23-33         |
| Wet clay                   | 3.0                          | 0.57  | 1.03  | 0.51  | 0.72                | 7      | 4        | 3.6    | 1,161.2           | 17, 23            |
| Saturated silty clay       | 3.0                          | 0.68  | 1.45  | 0.71  | 1.77                | 17     | 5        | 3.6    | 90.7              | 34                |

Note: For the completeness of the data list, those TNT cratering data not used in the statistical analysis are presented in Appendixes B and C and found in References 35-37.

APPENDIX A: CRATER DIMENSIONS FROM SINGLE HIGH-EXPLOSIVE  
CHARGE DETONATIONS IN ROCK

Table A1  
Crater Dimensions from Single High-Explosive Charge Detonations in Rock

| Series Name                                  | Shot Designation | Sponsor  | Date      | Medium              | Type of Explosive | Charge     |           |                | Apparent Crater |           |                       | Source |
|--|------------------|--|-----------|---------------------|-------------------|------------|-----------|----------------|-----------------|-----------|-----------------------|--------|
|  |                  |  |           |                     |                   | Weight lb  | Weight kg | Burial Depth m | Radius m        | Depth m   | Volume m <sup>3</sup> |        |
| Isthmian Canal Study                         | 1                | Panama Canal Zone Special Engineering Division | Nov 1946- | Basalt              | TNT               | 8          | 3.63      | 0.91           | 0.98            | 0.33      | 1.00                  | 11     |
|  | 2                |  | Apr 1947  |                     |                   | 75         | 34.02     | 1.22           | 1.06            | 0.21      | 0.98                  |        |
|  | 3                |  | 75        |                     |                   | 34.02      | 1.83      | 2.11           | 1.05            | 5.98      |                       |        |
|  | 4                |  | 25        |                     |                   | 11.34      | 1.83      | 2.02           | 0.88            | 2.80      |                       |        |
|  | 5*               |  | 25        |                     |                   | 11.34      | 2.29      | --             | --              | Mound     |                       |        |
|  | 6                |  | 25        |                     |                   | 11.34      | 1.37      | 0.89           | 0.26            | 0.47      |                       |        |
|  | 7                |  | 25        |                     |                   | 11.34      | 2.74      | 1.07           | 0.70            | 0.41      |                       |        |
|  | 8                |  | 8         |                     |                   | 3.63       | 2.13      | 0.72           | 0.32            | 0.43      |                       |        |
|  | 9                |  | 25        |                     |                   | 11.34      | 0.91      | 0.72           | 0.37            | 0.32      |                       |        |
|  | 10               |  | 25        |                     |                   | 11.34      | 3.20      | 0.58           | 0.19            | 0.05      |                       |        |
|  | 11*              |  | 75        |                     |                   | 34.02      | 3.81      | --             | --              | Mound     |                       |        |
|  | 12               |  | 200       |                     |                   | 90.72      | 3.66      | 2.90           | 1.21            | 15.49     |                       |        |
|  | 13               |  | 25        |                     |                   | 11.34      | 0.46      | 1.40           | 0.93            | 2.42      |                       |        |
|  | 14               |  | 25        |                     |                   | 11.34      | 0.00      | 0.61           | 0.22            | 0.16      |                       |        |
|  | 15               |  | 200       |                     |                   | 90.72      | 0.00      | 1.42           | 0.49            | 1.40      |                       |        |
|  | 16               |  | Dec 1947- |                     |                   |            |           |                |                 |           |                       |        |
|  | 17               |  | Mar 1948  |                     |                   | 200        | 90.72     | 0.00           | 1.62            | 0.37      | 1.78                  |        |
|  | 18               |  |           |                     |                   | 200        | 90.72     | 0.37           | 1.69            | 0.40      | 1.22                  |        |
|  |                  |  |           |                     |                   | 200        | 90.72     | 0.37           | 1.13            | 0.34      | 0.85                  |        |
| Isthmian Canal Study                         | 1                | Panama Canal Zone Special Engineering Division |           | Sandstone           | TNT               | 25         | 11.34     | 2.27           | 0.33            | 0.12      | 0.27                  | 15     |
|  | 2                |  | 8         |                     |                   | 3.63       | 0.91      | 1.17           | 0.53            | 1.12      |                       |        |
|  | 3                |  | 8         |                     |                   | 3.63       | 1.52      | 1.29           | 0.27            | 0.68      |                       |        |
|  | 4                |  | 75        |                     |                   | 34.02      | 3.66      | 0.16           | 0.30            | 0.02      |                       |        |
|  | 5*               |  | 8         |                     |                   | 3.63       | 2.13      | --             | --              | Mound     |                       |        |
|  | 6                |  | 75        |                     |                   | 34.02      | 1.22      | 2.56           | 1.37            | 12.14     |                       |        |
|  | 7*               |  | 25        |                     |                   | 11.34      | 2.74      | --             | --              | Mound     |                       |        |
|  | 8*               |  | 25        |                     |                   | 11.34      | 3.20      | --             | --              | Mound     |                       |        |
|  | 9                |  | 25        |                     |                   | 11.34      | 0.46      | 1.57           | 0.68            | 2.50      |                       |        |
|  | 10               |  | 200       |                     |                   | 90.72      | 3.54      | 1.51           | 0.37            | 5.36      |                       |        |
|  | 11               |  | 8         |                     |                   | 3.63       | 0.30      | 1.06           | 0.39            | 0.70      |                       |        |
|  | 12               |  | 25        |                     |                   | 11.34      | 1.83      | 1.42           | 0.42            | 2.22      |                       |        |
|  | 13               |  | 25        |                     |                   | 11.34      | 1.37      | 0.91           | 0.43            | 1.71      |                       |        |
|  | 14               |  | 25        |                     |                   | 11.34      | 0.91      | 1.50           | 0.40            | 1.29      |                       |        |
|  | 15               |  | 25        |                     |                   | 11.34      | 0.00      | 1.05           | 0.26            | 0.54      |                       |        |
| Isthmian Canal Study                         | 1                | Panama Canal Zone Special Engineering Division | Apr 1948  | Cucaracha formation | TNT               | 25         | 11.34     | 2.29           | 1.91            | 0.46      | 3.46                  | 16     |
|  | 2                |  | 8         |                     |                   | 3.63       | 1.22      | 1.88           | 0.78            | 3.91      |                       |        |
|  | 3                |  | ↓         |                     |                   | ↓          | 0.91      | 1.79           | 0.73            | 1.08      |                       |        |
|  | 4                |  | ↓         |                     |                   | ↓          | 0.61      | 1.56           | 0.61            | 2.35      |                       |        |
|  | 5                |  | ↓         |                     |                   | ↓          | 2.13      | 1.26           | 0.37            | 0.80      |                       |        |
|  | 6                |  | ↓         |                     |                   | ↓          | 1.53      | 1.52           | 0.52            | 2.16      |                       |        |
|  | 7                |  | ↓         |                     |                   | ↓          | 0.30      | 1.22           | 0.56            | 1.33      |                       |        |
|  | 8                |  | ↓         |                     |                   | ↓          | 1.83      | 1.86           | 0.87            | 5.15      |                       |        |
|  | 9                |  | 25        |                     |                   | 11.34      | 0.46      | 1.94           | 0.81            | 4.76      |                       |        |
|  | 10               |  | 25        |                     |                   | 11.34      | 1.37      | 2.90           | 0.99            | 11.54     |                       |        |
|  | 11               |  | 200       |                     |                   | 90.72      | 3.66      | 3.94           | 1.31            | 35.48     |                       |        |
|  | 12               |  | 75        |                     |                   | 34.02      | 3.66      | 3.03           | 0.72            | 13.61     |                       |        |
|  | 13               |  | 25        |                     |                   | 11.34      | 0.00      | 1.12           | 0.55            | 1.10      |                       |        |
|  | 14               |  | 50        |                     |                   | 22.68      | 0.00      | 2.29           | 0.94            | 6.69      |                       |        |
|  | 15               |  | 50        |                     |                   | 22.68      | 0.00      | 2.68           | 1.16            | --        |                       |        |
|  | 16               |  | 50        |                     |                   | 22.68      | 0.18      | 2.21           | 0.79            | 4.97      |                       |        |
| Dugway (Under-ground Explosion Test Program) | 501*             | Department of Defense                          |           | Limestone           | TNT               | 320        | 145.10    | 2.01           | 3.41            | 2.77      | 33.98                 | 12     |
|  | 502*             |  | ↓         |                     |                   | ↓          | 0.76      | 2.53           | 1.19            | 7.99      |                       |        |
|  | 601*             |  | ↓         |                     |                   | ↓          | -0.76     | 0.37           | 0.05            | --        |                       |        |
|  | 602              |  | ↓         |                     |                   | ↓          | 0.00      | 2.57           | 0.52            | 3.60      |                       |        |
| 603  | ↓                | ↓  | 0.76      | 2.96                | 0.79              | 7.42       |           |                |                 |           |                       |        |
| 604  | ↓                | ↓  | 1.52      | 4.42                | 1.52              | 31.43      |           |                |                 |           |                       |        |
| 605  | ↓                | ↓  | 3.81      | 5.21                | 1.86              | 52.67      |           |                |                 |           |                       |        |
| 606  | ↓                | ↓  | 7.62      | 1.58                | 0.61              | 1.65       |           |                |                 |           |                       |        |
| 607  | ↓                | ↓  | 0.76      | 4.39                | 1.62              | 32.28      |           |                |                 |           |                       |        |
| 608  | ↓                | ↓  | 0.76      | 4.27                | 1.40              | 26.82      |           |                |                 |           |                       |        |
| 609  | 2,560            | 1,161.20                                       | 1.52      | 7.68                | 3.11              | 192.55     |           |                |                 |           |                       |        |
| 610  | 2,560            | 1,161.20                                       | 1.52      | 7.04                | 2.65              | 138.19     |           |                |                 |           |                       |        |
| 611  | 320              | 145.10   | 0.76      | 4.08                | 1.52              | 26.45      |           |                |                 |           |                       |        |
| 612  | 320              | 145.10   | 5.18      | 4.02                | 2.32              | 39.64      |           |                |                 |           |                       |        |
| Dugway (Under-ground Explosion Test Program) | 801*             | Department of Defense                          |           | Sandstone           | TNT               | 320        | 145.10    | -0.76          | --              | --        | --                    | 13     |
|  | 802              |  | 320       |                     |                   | 145.10     | 0.00      | 1.71           | 0.70            | 4.59      |                       |        |
|  | 809              |  | 1,080     |                     |                   | 489.90     | 1.14      | 5.79           | 2.62            | 59.96     |                       |        |
|  | 812              |  | 2,560     |                     |                   | 1,161.20   | 1.52      | 7.10           | 3.35            | 195.10    |                       |        |
|  | 813              |  | 10,000    |                     |                   | 4,535.90   | 2.41      | 12.01          | 4.91            | 622.97    |                       |        |
|  | 815              |  | 40,000    |                     |                   | 18,143.70  | 3.81      | 21.49          | 8.20            | 3,539.61  |                       |        |
|  | 816              |  | 40,000    |                     |                   | 18,143.70  | 3.81      | 16.34          | 8.38            | 3,001.59  |                       |        |
|  | 817              |  | 320,000   |                     |                   | 145,149.60 | 7.62      | 28.90          | 14.33           | 14,498.23 |                       |        |
|  | 818              |  | 320       |                     |                   | 145.10     | 0.76      | 5.33           | 1.83            | 51.54     |                       |        |
|  | 819              |  | ↓         |                     |                   | ↓          | 0.76      | 4.75           | 1.98            | 40.78     |                       |        |
|  | 803              |  | ↓         |                     |                   | ↓          | 0.76      | 3.54           | 1.46            | 22.94     |                       |        |
|  | 804              |  | 13 Nov 51 |                     |                   | ↓          | ↓         | 1.52           | 4.27            | 0.62      | 40.78                 |        |
|  | 805*             |  | 6 Nov 51  |                     |                   | ↓          | ↓         | 3.81           | 2.83            | 4.54      | 33.70                 |        |
|  | 807              |  | 15 Apr 52 |                     |                   | ↓          | ↓         | 0.76           | 4.36            | 1.55      | 41.34                 |        |
|  | 808              |  | 3 May 52  |                     |                   | ↓          | ↓         | 0.76           | 3.99            | 1.77      | 45.87                 |        |

(Continued)

\* Data not used in the statistical analysis.

Table A1 (Concluded)

| Series Name           | Shot Designation | Sponsor                       | Date        | Medium             | Type of Explosive | Charge       |              | Burial Depth<br>m | Apparent Crater |            |                          | Source |          |
|-----------------------|------------------|-------------------------------|-------------|--------------------|-------------------|--------------|--------------|-------------------|-----------------|------------|--------------------------|--------|----------|
|                       |                  |                               |             |                    |                   | Weight<br>lb | Weight<br>kg |                   | Radius<br>m     | Depth<br>m | Volume<br>m <sup>3</sup> |        |          |
| Dugway<br>(Continued) | 810              | Department of Defense         | 9 Apr 52    | Sandstone          | TNT               | 2,560        | 1,161.20     | 1.52              | 9.94            | 2.96       | 244.94                   | 13     |          |
|                       | 811              |                               | 30 Apr 52   |                    |                   | 2,560        | 1,161.20     | 1.52              | 7.65            | 3.20       | 199.63                   |        |          |
|                       | 814              |                               | 4 Jun 52    |                    |                   | 40,000       | 18,143.70    | 3.81              | 17.22           | 8.20       | 3,058.22                 |        |          |
|                       | 806*             |                               | --          |                    |                   |              | 320          | 145.10            | 7.62            | --         | --                       |        |          |
| Tuff                  | 1                | Sandia Laboratories           | Spring 1959 | Tuff               | TNT               | 256          | 116.10       | 2.25              | 4.57            | 1.49       | 35.85                    | 14     |          |
|                       | 2                |                               |             |                    |                   |              |              | 2.93              | 4.24            | 1.28       | 31.15                    |        |          |
|                       | 6                |                               |             |                    |                   |              |              | 2.11              | 3.57            | 1.31       | 16.74                    |        |          |
|                       | 7                |                               |             |                    |                   |              |              | 3.16              | 2.10            | 0.70       | 3.17                     |        |          |
|                       | 11               |                               |             |                    |                   |              |              | 2.84              | 3.54            | 0.55       | 10.11                    |        |          |
| Buckboard             | 1*               |                               | 23 Jun 60   | Basalt             | TNT               | 1,000        | 453.60       | 7.50              | --              | --         | --                       | 9      |          |
|                       | 2                |                               | 21 Jun 60   | (Nevada Test Site) |                   |              |              | 5.76              | 1.41            | 0.43       | 1.27                     |        |          |
|                       | 3                |                               | 30 Jun 60   |                    |                   |              |              | 4.48              | 4.77            | 1.58       | 50.97                    |        |          |
|                       | 4                |                               | 16 Aug 60   |                    |                   |              |              | 2.93              | 5.09            | 1.98       | 74.19                    |        |          |
|                       | 5                |                               | 1 Jul 60    |                    |                   |              |              | 1.46              | 4.57            | 2.29       | 53.52                    |        |          |
|                       | 6                |                               | 27 Jun 60   |                    |                   |              |              | 7.32              | 1.86            | 1.58       | 5.24                     |        |          |
|                       | 7                |                               | 30 Jun 60   |                    |                   |              |              | 5.67              | 3.25            | 1.16       | 18.52                    |        |          |
|                       | 8                |                               | 24 Jun 60   |                    |                   |              |              | 4.48              | 5.16            | 2.68       | 99.11                    |        |          |
|                       | 9                |                               | 16 Aug 60   |                    |                   |              |              | 2.93              | 3.70            | 1.46       | 22.65                    |        |          |
|                       | 10               |                               | 6 Jul 60    |                    |                   |              |              | 1.46              | 4.82            | 2.13       | 75.32                    |        |          |
|                       | 11               |                               | 14 Sep 60   |                    |                   |              | 40,000       | 18,143.70         | 7.77            | 13.61      | 7.59                     |        | 1,535.34 |
|                       | 12               |                               | 27 Sep 60   |                    |                   |              | 40,000       | 18,143.70         | 13.01           | 17.37      | 10.58                    |        | 3,822.77 |
|                       | 13               |                               | 24 Aug 60   |                    |                   |              | 40,000       | 18,143.70         | 17.92           | 11.22      | 4.94                     |        | 656.95   |
| OSO                   | 1*               | Boeing Company                | Aug 1963    | Argillite          | TNT               | 64           | 29.03        | 0.00              | 1.16            | 0.43       | 1.58                     | 10     |          |
|                       | 2*               |                               |             |                    |                   |              |              | 0.00              | 1.43            | 0.49       | 1.58                     |        |          |
| Flat Top              | 1*               | Defense Atomic Support Agency | 22 Jun 64   | Limestone          | TNT               | 40,000       | 18,144.00    | 0.00              | 8.23            | 3.87       | 283.17                   | 24     |          |
| MICE                  | S1 (C1)          | Air Force                     | 21 Jun 65   | Basalt             | TNT               | 4,000        | 1,814.40     | 0.00              | 3.69            | 1.10       | 20.76                    | 10     |          |
|                       | S2a              | Weapons                       | 17 Jun 65   |                    |                   | 4,000        | 1,814.40     | 0.00              | 3.26            | 1.22       | 19.03                    |        |          |
|                       | S3a              | Laboratory                    | 16 Jul 65   |                    |                   | 4,000        | 1,814.40     | 0.00              | 3.47            | 1.22       | 24.15                    |        |          |
|                       | S4a              |                               | 10 Jul 65   |                    |                   | 4,000        | 1,814.40     | 0.00              | 3.17            | 1.22       | 17.13                    |        |          |
|                       | LS               |                               | 8 Jul 65    |                    |                   | 16,000       | 7,257.60     | 0.00              | 5.70            | 1.71       | 103.61                   |        |          |
|                       | C2               |                               | 25 Jun 63   | Basalt             | TNT               | 4,000        | 1,814.40     | 0.67              | 4.27            | 1.62       | 42.48                    |        |          |
|                       | St 1*            |                               | 11 Jun 65   | (Yamika)           |                   | 4,000        | 1,814.40     | -0.67             | 1.13            | 0.40       | 1.05                     |        |          |
|                       | St 2a*           |                               | 14 Jul 65   | Firing Center,     |                   | 4,000        | 1,814.40     | -0.67             | 2.07            | 0.58       | 3.94                     |        |          |
| St 3a*                |                  | 23 Jun 65                     |             |                    | 4,000             | 1,814.40     | -0.67        | 1.37              | 0.37            | 0.71       |                          |        |          |

\* Data not used in the statistical analysis.

APPENDIX B: CRATER DIMENSIONS FROM SINGLE HIGH-EXPLOSIVE  
CHARGE DETONATIONS IN SOIL

Table B1  
 Crater Dimensions from Single High-Explosive Charge Detonations in Soil

| Series Name          | Shot Designation | Sponsor   | Date      | Medium                              | Type of Explosive | Charge    |                       |                | Apparent Crater |              |                       | Source   |           |
|----------------------|------------------|---|-----------|-------------------------------------|-------------------|-----------|-----------------------|----------------|-----------------|--------------|-----------------------|----------|-----------|
|                      |                  |   |           |                                     |                   | Weight lb | Weight kg             | Burial Depth m | Radius m        | Depth m      | Volume m <sup>3</sup> |          |           |
| Isthmian Canal Study | 1                | Panama Canal Zone Special Engineering Division    | 1948      | Marine muck                         | TNT               | 8         | 3.63                  | 0.30           | 1.59            | 1.30         | 6.57                  | 34       |           |
|                      | 2                |   |           |                                     |                   | 8         | 3.63                  | 0.91           | 2.01            | 1.55         | 7.29                  |          |           |
|                      | 3                |   |           |                                     |                   | 8         | 3.63                  | 1.52           | 2.71            | 0.49         | 4.62                  |          |           |
|                      | 4                |   |           |                                     |                   | 8         | 3.63                  | 2.13           | 1.38            | 0.96         | 3.91                  |          |           |
|                      | 5                |   |           |                                     |                   | 25        | 11.34                 | 0.46           | 2.70            | 2.03         | 19.89                 |          |           |
|                      | 6                |   |           |                                     |                   | ↓         | ↓                     | 0.91           | 2.77            | 2.01         | 24.82                 |          |           |
|                      | 7                |   |           |                                     |                   | ↓         | ↓                     | 1.37           | 2.36            | 1.89         | 20.90                 |          |           |
|                      | 8                |   |           |                                     |                   | ↓         | ↓                     | 1.83           | 1.99            | 1.84         | 16.25                 |          |           |
|                      | 9                |   |           |                                     |                   | ↓         | ↓                     | 2.29           | 3.34            | 0.91         | 12.62                 |          |           |
|                      | 10               |   |           |                                     |                   | ↓         | ↓                     | 2.74           | 3.61            | 0.60         | 11.38                 |          |           |
|                      | 11               |   |           |                                     |                   | ↓         | ↓                     | 3.20           | 3.43            | 0.89         | 8.25                  |          |           |
|                      | 12               |   |           |                                     |                   | 75        | 34.02                 | 1.22           | 3.83            | 2.83         | 57.53                 |          |           |
|                      | 13               |   |           |                                     |                   | 75        | 34.02                 | 3.66           | 5.95            | 0.80         | 37.21                 |          |           |
|                      | 14*              |   |           |                                     |                   | 200       | 90.72                 | 3.66           | 10.09           | 0.76         | 96.43                 |          |           |
|                      | 15               |   |           |                                     |                   | 25        | 11.34                 | 0.00           | 1.73            | 1.18         | 6.15                  |          |           |
|                      | 16(1A)           |   |           |                                     |                   | 50        | 22.68                 | 0.00           | 2.19            | 1.52         | 13.69                 |          |           |
|                      | 17(2A)           |   |           |                                     |                   | 50        | 22.68                 | 0.00           | 2.33            | 1.52         | 13.00                 |          |           |
| Isthmian Canal Study | 1                | Panama Canal Zone Special Engineering Division    |           | Residual clay (wet)                 | TNT               | 25        | 11.34                 | 0.46           | 1.43            | 0.90         | 2.65                  | 35       |           |
|                      | 2                |   |           |                                     |                   | 75        | 34.02                 | 3.66           | 3.76            | 0.59         | 10.59                 |          |           |
|                      | 3                |   |           |                                     |                   | 8         | 3.63                  | 1.52           | 1.33            | 0.51         | 1.38                  |          |           |
|                      | 4                |   |           |                                     |                   | 75        | 34.02                 | 2.44           | 3.34            | 1.52         | 21.17                 |          |           |
|                      | 5                |   |           |                                     |                   | 200       | 90.72                 | 1.83           | 5.16            | 2.87         | 100.49                |          |           |
|                      | 6                |   |           |                                     |                   | 25        | 11.34                 | 0.00           | 1.16            | 0.64         | 0.93                  |          |           |
|                      | 7                |   |           |                                     |                   | 25        | 11.34                 | 1.37           | 2.21            | 0.97         | 6.03                  |          |           |
|                      | 8                |   |           |                                     |                   | 8         | 3.63                  | 2.13           | 1.07            | 0.76         | 1.59                  |          |           |
| Jangle - HE          | HE-1             | Department of Defense/Stanford Research Institute | 25 Aug 51 | Alluvium (Nevada Test Site Area 10) | TNT               | 2,560     | 1,161.20              | 0.62           | 5.64            | 2.04         | 56.92                 | 18       |           |
|                      | HE-2             |   |           |                                     |                   | 40,000    | 18,143.70             | 1.56           | 11.89           | 4.57         | 991.09                |          |           |
|                      | HE-3             |   |           |                                     |                   | 2,560     | 1,161.20              | 2.08           | 6.18            | 3.29         | 169.90                |          |           |
|                      | HE-4*            |   |           |                                     |                   | ↓         | ↓                     | -0.62          | 2.10            | 0.58         | 3.11                  |          |           |
|                      | HE-5             |   |           |                                     |                   | 1.25      | 5.91                  | 2.29           | 113.27          |              |                       |          |           |
|                      | HE-6             |   |           |                                     |                   | 2 Oct 51  | ↓                     | ↓              | 0.92            | 6.04         | 1.86                  |          | 101.94    |
|                      | HE-7             |   |           |                                     |                   | 4 Oct 51  | ↓                     | ↓              | 0.79            | 5.79         | 2.04                  |          | 93.45     |
|                      | HE-8*            |   |           |                                     |                   | 13 Oct 51 | 216                   | 98.00          | 0.33            | Not measured |                       |          |           |
|                      | 8-A*             |   |           |                                     |                   | ↓         | 177                   | 80.10          | 0.33            | 2.76         | 1.04                  |          | 7.67      |
|                      | HE-9             |   |           |                                     |                   | 14 Oct 51 | 216                   | 98.00          | 0.26            | 2.53         | 1.22                  |          | 7.65      |
|                      | 9-A*             |   |           |                                     |                   | ↓         | 177                   | 80.10          | 0.26            | 2.67         | 1.07                  |          | 7.22      |
| HE-10                | 14 Oct 51        | 216   | 98.00     | 0.91                                | 3.44              | 1.68      | 24.35                 |                |                 |              |                       |          |           |
| 10-A*                | ↓                | 177   | 80.10     | 0.91                                | 3.09              | 1.52      | 14.16                 |                |                 |              |                       |          |           |
| Dugway               | 301*             | Department of Defense                             | 29 Mar 51 | Dry clay (Utah)                     | TNT               | 320       | 145.15                | -1.07          | 0.76            | 0.30         | --                    | 23       |           |
|                      | 302              |   |           |                                     |                   | ↓         | ↓                     | 0.00           | 2.21            | 1.22         | 6.80                  |          |           |
|                      | 303              |   |           |                                     |                   | 2 Apr 51  | ↓                     | ↓              | 0.40            | 2.74         | 1.68                  |          | 16.99     |
|                      | 304              |   |           |                                     |                   | 4 Apr 51  | ↓                     | ↓              | 1.07            | 3.20         | 1.83                  |          | 23.22     |
|                      | 305              |   |           |                                     |                   | 6 Apr 51  | ↓                     | ↓              | 2.13            | 3.58         | 2.13                  |          | 36.81     |
|                      | 306              |   |           |                                     |                   | 12 Apr 51 | ↓                     | ↓              | 4.27*           | 4.57         | 0.30                  |          | 6.68      |
|                      | 307              |   |           |                                     |                   | 10 Apr 51 | ↓                     | ↓              | 6.40            | 3.05         | 0.30                  |          | 2.83      |
|                      | 308              |   |           |                                     |                   | 16 Apr 51 | 2,560                 | 1,161.22       | 7.90            | 6.10         | 3.66                  |          | 152.91    |
|                      | 309              |   |           |                                     |                   | 18 Apr 51 | 2,560                 | 1,161.22       | 2.13            | 6.55         | 4.72                  |          | 206.71    |
|                      | 310              |   |           |                                     |                   | 23 Apr 51 | 320                   | 145.15         | 1.07            | 3.35         | 2.13                  |          | 25.49     |
|                      | 312              |   |           |                                     |                   | 4 May 51  | 2,560                 | 1,161.22       | 2.13            | 7.92         | 4.57                  |          | 368.12    |
|                      | 315              |   |           |                                     |                   | 10 May 51 | 40,000                | 18,143.70      | 5.33            | 19.51        | 12.80                 |          | 5,380.20  |
|                      | 318              |   |           |                                     |                   | ↓         | 320,000               | 145,149.60     | 10.67           | 36.58        | 18.29                 |          | 31,148.55 |
|                      | 311              |   |           |                                     |                   | ↓         | 8                     | 3.63           | 0.61            | 1.22         | 0.76                  |          | 1.87      |
|                      | 314              |   |           |                                     |                   | ↓         | 8                     | 3.63           | 0.76            | 1.37         | 0.91                  |          | 2.44      |
|                      | 316              |   |           |                                     |                   | 110       | 49.90                 | 0.75           | 2.74            | 1.83         | 20.95                 |          |           |
|                      | 313              |   |           |                                     |                   | 320       | 145.15                | 1.07           | 3.89            | 2.44         | 42.48                 |          |           |
|                      | 317              |   |           |                                     |                   | 2,560     | 1,161.22              | 2.13           | 7.01            | 4.72         | 311.49                |          |           |
|                      | 319              |   |           |                                     |                   | 2,560     | 1,161.22              | 2.13           | 7.01            | 4.11         | 220.87                |          |           |
|                      | Symmetry         |   |           |                                     |                   | 320       | 145.15                | 2.13           | 3.81            | 2.13         | 36.81                 |          |           |
|                      | Dugway           |   |           |                                     |                   | 101*      | Department of Defense | 7 Jun 51       | Dry sand        | TNT          | 320                   |          | 145.15    |
| 102                  |                  | ↓   | ↓         | 0.00                                | 2.33              | 0.76      |                       |                |                 |              | 7.08                  |          |           |
| 103                  |                  | 7 Jun 51  | ↓         | ↓                                   | 0.40              | 3.32      |                       |                |                 |              | 1.83                  | 20.39    |           |
| 104                  |                  | 7 Jun 51  | ↓         | ↓                                   | 1.07              | 3.66      |                       |                |                 |              | 1.98                  | 36.81    |           |
| 105                  |                  | 19 Jun 51   | ↓         | ↓                                   | 2.13              | 4.72      |                       |                |                 |              | 2.59                  | 73.62    |           |
| 106                  |                  | 27 Jun 51   | ↓         | ↓                                   | 4.27              | 5.11      |                       |                |                 |              | 1.37                  | 31.15    |           |
| 107                  |                  | 27 Jun 51   | ↓         | ↓                                   | 6.40              | 4.11      |                       |                |                 |              | 1.07                  | 22.37    |           |
| 108                  |                  | 10 Jul 51   | 2,560     | 1,161.22                            | 0.79              | 5.79      |                       |                |                 |              | 2.97                  | 147.25   |           |
| 109                  |                  | 10 Jul 51   | 2,560     | 1,161.22                            | 2.13              | 7.54      |                       |                |                 |              | 2.59                  | 232.20   |           |
| 110                  |                  | 13 Aug 51   | 320       | 145.15                              | 1.07              | 3.96      |                       |                |                 |              | 2.29                  | 45.31    |           |
| 112                  |                  | 27 Jul 51   | 2,560     | 1,161.22                            | 2.13              | 9.14      |                       |                |                 |              | 3.67                  | 368.12   |           |
| 115                  |                  | 8 Aug 51  | 40,000    | 18,143.70                           | 5.33              | 22.86     |                       |                |                 |              | 7.01                  | 5,097.03 |           |
| 111*                 |                  | 8   | 3.63      | 0.76                                | 1.83              | 1.22      |                       |                |                 |              | 3.96                  |          |           |
| 113                  |                  | 320   | 145.15    | 1.07                                | 4.27              | 2.06      |                       |                |                 |              | 53.80                 |          |           |
| 114*                 |                  | 8   | 3.63      | 0.76                                | 1.83              | 1.07      |                       |                |                 |              | 4.25                  |          |           |
| 116                  |                  | 320   | 145.15    | 2.67                                | 5.64              | 2.74      |                       |                |                 |              | 99.11                 |          |           |
| 0.029A-15*           | 8                | 3.63  | 0.76      | --                                  | --                | --        |                       |                |                 |              |                       |          |           |
| 0.04A-16*            | 20               | 9.07  | 0.76      | --                                  | --                | --        |                       |                |                 |              |                       |          |           |
| 0.05A-17*            | 40               | 18.14   | 0.76      | --                                  | --                | --        |                       |                |                 |              |                       |          |           |
| Dugway               | 402              | Department of Defense                             | 23 Aug 51 | Wet clay (Utah)                     | TNT               | 320       | 145.15                | 0.76           | 5.72            | 3.05         | 116.10                | 23       |           |
|                      | 403              |   |           |                                     |                   | 2,560     | 1,161.22              | 1.52           | 12.73           | 3.89         | 821.19                |          |           |
|                      | 401              |   |           |                                     |                   | 8         | 3.63                  | 0.76           | 2.13            | 1.52         | 8.78                  |          |           |
|                      | 405              |   |           |                                     |                   | 8         | 3.63                  | 0.76           | 1.83            | 1.25         | 7.65                  |          |           |
|                      | 404              |   |           |                                     |                   | 21 Aug 51 | 320                   | 145.15         | 0.76            | 5.33         | 3.51                  |          | 110.44    |

(Continued)

\* Data not used in the statistical analysis.

Table B1 (Continued)

| Series Name      | Shot Designation | Sponsor             | Date                | Medium                              | Type of Explosive      | Charge    |           |                         | Apparent Crater                     |         |                       | Source |        |      |      |       |       |    |
|------------------|------------------|---------------------|---------------------|-------------------------------------|------------------------|-----------|-----------|-------------------------|-------------------------------------|---------|-----------------------|--------|--------|------|------|-------|-------|----|
|                  |                  |                     |                     |                                     |                        | Weight lb | Weight kg | Burial Depth m          | Radius m                            | Depth m | Volume m <sup>3</sup> |        |        |      |      |       |       |    |
| Mole             | 101              | Armed Forces        | 28 Jun 52           | Dry clay (Utah)                     | TNT                    | 256       | 116.12    | 1.94                    | 3.22                                | 1.65    | 21.02                 | 17     |        |      |      |       |       |    |
|                  | 102              | Special             |                     |                                     |                        |           |           | 0.97                    | 3.12                                | 1.95    | 22.95                 |        |        |      |      |       |       |    |
|                  | 102A             | Weapons             | 6 Jul 52            |                                     |                        |           |           | 0.97                    | 2.93                                | 1.63    | 16.66                 |        |        |      |      |       |       |    |
|                  | 105              | Project/Stanford    | 13 Jun 52           |                                     |                        |           |           | 1.94                    | 3.29                                | 1.77    | 24.26                 |        |        |      |      |       |       |    |
|                  | 106              | Research            | 19 Jul 52           |                                     |                        |           |           | 0.50                    | 2.77                                | 1.89    | 15.24                 |        |        |      |      |       |       |    |
|                  | 107              | Institute           | 20 Aug 52           |                                     |                        |           |           | 0.00                    | 2.01                                | 1.19    | 6.57                  |        |        |      |      |       |       |    |
|                  | 311              |                     | 20 Oct 53           |                                     |                        |           |           | Moist clay (California) | TNT                                 | 256     | 116.12                |        | 0.97   | 4.72 | 3.41 | 89.13 |       |    |
|                  | 312              |                     | 22 Oct 53           |                                     |                        |           |           |                         |                                     |         |                       |        | 0.97   | 5.33 | 2.77 | 94.73 |       |    |
| Mole             | 301*             | Armed Forces        | 15 Sep 53           | Wet sand                            | TNT                    | 256       | 116.12    | --                      | --                                  | --      | --                    | 17     |        |      |      |       |       |    |
|                  | 302              | Special             | 18 Sep 53           |                                     |                        |           |           | 0.97                    | 6.10                                | 1.89    | 95.92                 |        |        |      |      |       |       |    |
|                  | 304              | Weapons             | 23 Sep 53           |                                     |                        |           |           | 1.45                    | 5.94                                | 2.01    | --                    |        |        |      |      |       |       |    |
|                  | 305              | Project/Stanford    | 26 Sep 53           |                                     |                        |           |           | 0.50                    | 4.91                                | 1.92    | 58.62                 |        |        |      |      |       |       |    |
|                  | 306              | Research            | 8 Oct 53            |                                     |                        |           |           | 0.25                    | 3.99                                | 1.16    | 38.94                 |        |        |      |      |       |       |    |
|                  | 307              | Institute           | 8 Oct 53            |                                     |                        |           |           | 0.00                    | 3.93                                | 1.43    | 37.30                 |        |        |      |      |       |       |    |
|                  | 308*             |                     | 10 Oct 53           |                                     |                        |           |           | -0.25                   | 2.71                                | 1.22    | 12.70                 |        |        |      |      |       |       |    |
|                  | 309              |                     | 16 Oct 53           |                                     |                        |           |           | 0.97                    | 5.09                                | 1.86    | 76.98                 |        |        |      |      |       |       |    |
|                  | 310              |                     | 17 Oct 53           |                                     |                        |           |           | 0.97                    | 5.33                                | 1.58    | 73.57                 |        |        |      |      |       |       |    |
|                  | Mole             | 202                 | Armed Forces        |                                     |                        |           |           | 14 Sep 52               | Alluvium (Nevada Test Site Area 10) | TNT     | 256                   |        | 116.10 | 1.94 | 3.44 | 1.68  | 29.59 | 17 |
| 203              |                  | Special             | 19 Sep 52           | 0.97                                | 2.55                   | 1.20      | 10.07     |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 204              |                  | Weapons             | 4 Oct 52            | 0.50                                | 2.88                   | 0.79      | 10.30     |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 205              |                  | Project/Stanford    | 8 Oct 52            | 0.25                                | 2.76                   | 0.62      | 8.49      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 206              |                  | Research            | 11 Oct 52           | 0.00                                | 1.94                   | 0.52      | 3.66      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 207*             |                  | Institute           | 15 Oct 52           | -0.25                               | 1.23                   | 0.43      | 1.06      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 212              |                  |                     | 24 Oct 52           | 1.94                                | 3.57                   | 1.78      | 34.18     |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 401              |                  |                     | 23 Oct 54           | 0.97                                | 3.23                   | 1.68      | 23.34     |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 402              |                  |                     | 26 Oct 54           | 1.45                                | 3.37                   | 1.89      | 26.69     |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 403              |                  |                     | 28 Oct 54           | 0.25                                | 2.53                   | 1.04      | 8.31      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 404              |                  |                     | 30 Oct 54           | 1.94                                | 3.58                   | 1.83      | 33.71     |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 405              |                  |                     | 2 Nov 54            | 0.50                                | 2.80                   | 1.39      | 14.11     |                         |                                     |         |                       |        |        |      |      |       |       |    |
| 406              |                  | 4 Nov 54            | 0.97                | 3.00                                | 1.22                   | 19.05     |           |                         |                                     |         |                       |        |        |      |      |       |       |    |
| Unnamed          | 209              | Sandia Laboratories | 1959                | Alluvium (Albuquerque)              | TNT                    | 256       | 116.10    | 3.87                    | +5.00                               | 1.16    | 26.76                 | 30     |        |      |      |       |       |    |
| Sandia Series I  | 2                | Sandia Laboratories | 21 Jan 59           | Alluvium (Nevada Test Site Area 10) | TNT                    | 256       | 116.10    | 2.90                    | 4.61                                | 2.40    | 60.77                 | 19     |        |      |      |       |       |    |
|                  | 3                |                     | 26 Jan 59           |                                     |                        |           |           | 4.85                    | 3.45                                | 0.54    | 10.42                 |        |        |      |      |       |       |    |
|                  | 8                |                     | 20 Jan 59           |                                     |                        |           |           | 1.94                    | 4.00                                | 2.23    | 42.16                 |        |        |      |      |       |       |    |
|                  | 9                |                     | 23 Jan 59           |                                     |                        |           |           | 2.90                    | 4.31                                | 2.18    | 54.65                 |        |        |      |      |       |       |    |
|                  | 10               |                     | 23 Jan 59           |                                     |                        |           |           | 3.87                    | 4.08                                | 1.25    | 30.95                 |        |        |      |      |       |       |    |
|                  | 11               |                     | 24 Jan 59           |                                     |                        |           |           | 4.85                    | 1.99                                | 0.12    | 6.68                  |        |        |      |      |       |       |    |
|                  | 12               |                     | 27 Jan 59           |                                     |                        |           |           | 5.81                    | 2.85                                | 0.70    | 7.25                  |        |        |      |      |       |       |    |
|                  | 15               |                     | 16 Dec 58?          |                                     |                        |           |           | 7.74                    | 1.27                                | 0.14    | 0.88                  |        |        |      |      |       |       |    |
|                  | 16               |                     |                     |                                     |                        |           |           | 3.87                    | 4.33                                | 2.04    | 62.86                 |        |        |      |      |       |       |    |
|                  | 17               |                     | 15 Dec 58?          |                                     |                        |           |           | 5.81                    | 1.73                                | 0.52    | 1.56                  |        |        |      |      |       |       |    |
| Sandia Series II | 1*               | Sandia Laboratories | Aug 59,             | Alluvium (Nevada Test Site Area 10) | TNT                    | 256       | 116.10    | 9.08                    | 9.45                                | -0.19   | -16.54                | 19     |        |      |      |       |       |    |
|                  | 2*               |                     | Sep 59              |                                     |                        |           |           | 8.69                    | 11.49                               | -0.25   | -30.55                |        |        |      |      |       |       |    |
|                  | 3*               |                     |                     |                                     |                        |           |           | 7.96                    | 9.85                                | -0.31   | -33.61                |        |        |      |      |       |       |    |
|                  | 4                |                     |                     |                                     |                        |           |           | 7.77                    | 0.72                                | 0.35    | 0.45                  |        |        |      |      |       |       |    |
|                  | 5                |                     |                     |                                     |                        |           |           | 7.10                    | 0.92                                | 0.09    | 0.51                  |        |        |      |      |       |       |    |
|                  | 6                |                     |                     |                                     |                        |           |           | 6.89                    | 1.34                                | 0.30    | 4.81                  |        |        |      |      |       |       |    |
|                  | 7                |                     |                     |                                     |                        |           |           | 6.00                    | 2.48                                | 0.31    | 3.43                  |        |        |      |      |       |       |    |
|                  | 8                |                     |                     |                                     |                        |           |           | 5.79                    | 3.07                                | 0.49    | 8.41                  |        |        |      |      |       |       |    |
|                  | 9                |                     |                     |                                     |                        |           |           | 5.00                    | 4.36                                | 0.80    | 20.27                 |        |        |      |      |       |       |    |
|                  | 10               |                     |                     |                                     |                        |           |           | 4.91                    | 4.30                                | 1.39    | 30.50                 |        |        |      |      |       |       |    |
|                  | 11               |                     |                     |                                     |                        |           |           | 3.99                    | 4.48                                | 1.66    | 47.29                 |        |        |      |      |       |       |    |
|                  | S-12             |                     |                     |                                     |                        |           |           | 0.00                    | 2.61                                | 0.76    | 4.56                  |        |        |      |      |       |       |    |
|                  | S-13             |                     |                     |                                     |                        |           |           | 0.00                    | 2.54                                | 0.79    | 7.56                  |        |        |      |      |       |       |    |
|                  | Toboggan         | E 1a                | Sandia Laboratories |                                     |                        |           |           | 23 Nov 59               | Playa (Yucca Lake)                  | TNT     | 8*                    |        | 3.63*  | 0.00 | 0.47 | 0.28  | 0.07  | 36 |
| E 1b             |                  |                     | 23 Nov 59           | 0.00                                | 0.45                   | 0.20      | 0.05      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 1c             |                  |                     | 24 Nov 59           | 0.00                                | 0.40                   | 0.20      | 0.04      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 2a             |                  |                     | 24 Nov 59           | 0.15                                | 0.78                   | 0.34      | 0.33      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 2b             |                  |                     | 24 Nov 59           | 0.15                                | 0.69                   | 0.32      | 0.23      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 2c             |                  |                     | 24 Nov 59           | 0.15                                | 0.74                   | 0.44      | 0.33      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 3a             |                  |                     | 24 Nov 59           | 0.30                                | 0.85                   | 0.49      | 0.44      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 3b             |                  |                     | 24 Nov 59           | 0.30                                | 0.92                   | 0.47      | 0.48      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 3c             |                  |                     | 24 Nov 59           | 0.30                                | 0.82                   | 0.53      | 0.44      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 3.5a           |                  |                     | 16 Jun 60           | 0.46                                | 0.87                   | 0.52      | 0.51      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 4a             |                  |                     | 24 Nov 59           | 0.61                                | 1.05                   | 0.54      | 0.75      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 4.5a           |                  |                     | 18 Jun 60           | 0.76                                | 1.14                   | 0.45      | 0.78      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 4b             |                  |                     | 24 Nov 59           | 0.61                                | 1.09                   | 0.59      | 0.97      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 4.5b           |                  |                     | 18 Jun 60           | 0.76                                | 1.01                   | 0.31      | 0.37      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 4c             |                  |                     | 24 Nov 59           | 0.61                                | 1.12                   | 0.55      | 1.03      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 5a             |                  |                     | 14 Nov 59           | 0.91                                | 1.12                   | 0.24      | 0.48      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 5b             |                  |                     | 15 Nov 59           | 0.91                                | 1.22                   | 0.55      | 1.10      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 5c             |                  |                     | 15 Nov 59           | 0.91                                | 1.12                   | 0.20      | 0.39      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 5.5a           |                  |                     | 18 Jun 60           | 1.07                                | 0.96                   | 0.10      | 0.20      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 6a             |                  |                     | 15 Nov 59           | 1.22                                | 0.58                   | 0.06      | 0.04      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 6b             |                  |                     | 15 Nov 59           | 1.22                                | 0.46                   | 0.04      | 0.01      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 6c             |                  |                     | 15 Nov 59           | 1.22                                | 0.73                   | 0.03      | 0.06      |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 6.5a           |                  |                     | 18 Jun 60           | 1.37                                | --                     | --        | --        |                         |                                     |         |                       |        |        |      |      |       |       |    |
| E 7a             |                  |                     | 18 Jun 60           | 1.52                                | --                     | --        | --        |                         |                                     |         |                       |        |        |      |      |       |       |    |
| Little Ditch     |                  | 1 C                 | Sandia Laboratories | 12 Nov 59                           | Alluvium (Albuquerque) | TNT       | 8*        | 3.63                    |                                     |         |                       | 0.30   |        | 0.85 | 0.37 | 0.33  | 25    |    |
|                  |                  | 1 C 8               |                     | 29 Jun 59                           |                        |           |           |                         |                                     |         |                       | 0.30   |        | 0.94 | 0.34 | 0.27  |       |    |
|                  | 1 D              |                     | 10 Nov 59           | 0.46                                |                        |           |           |                         | 1.08                                | 0.43    | 0.58                  |        |        |      |      |       |       |    |
|                  | IV 1-1.5         |                     | 11 Apr 60           | 0.46                                |                        |           |           |                         | 1.18                                | 0.3     | 0.63                  |        |        |      |      |       |       |    |
|                  | IV 2-1.5         |                     | 14 Apr 60           | 0.46                                |                        |           |           |                         | 1.07                                | 0.21    | 0.28                  |        |        |      |      |       |       |    |
|                  |                  |                     |                     | 0.46                                |                        |           |           |                         | 1.07                                | 0.21    | 0.28                  |        |        |      |      |       |       |    |

(Continued)

Table B1 (Continued)

| Series Name              | Shot Designation | Sponsor                 | Date      | Medium                              | Type of Explosive | Charge    |            | Apparent Crater |          |          |                       | Source |      |       |  |
|--------------------------|------------------|-------------------------|-----------|-------------------------------------|-------------------|-----------|------------|-----------------|----------|----------|-----------------------|--------|------|-------|--|
|                          |                  |                         |           |                                     |                   | Weight lb | Weight Kg  | Burial Depth m  | Radius m | Depth m  | Volume m <sup>3</sup> |        |      |       |  |
| Little Ditch (Continued) | IV 3-1.5         | Sandia Laboratories     | 18 Apr 60 | Alluvium (Albuquerque)              | TNT               | 8*        | 3.63       | 0.46            | 1.14     | 0.18     | 0.35                  | 25     |      |       |  |
|                          | IV 4-1.5         |                         | 19 Apr 60 |                                     |                   |           |            | 0.46            | 1.05     | 0.18     | 0.26                  |        |      |       |  |
|                          | IV 5-1.5         |                         | 21 Apr 60 |                                     |                   |           |            | 0.46            | 0.96     | 0.12     | 0.10                  |        |      |       |  |
|                          | IV 6-1.5         |                         | 25 Apr 60 |                                     |                   |           |            | 0.46            | 1.05     | 0.37     | 0.42                  |        |      |       |  |
|                          | IV 7-1.5         |                         | 27 Apr 60 |                                     |                   |           |            | 0.46            | 1.10     | 0.55     | 0.76                  |        |      |       |  |
|                          | IV 8-1.5         |                         | 28 Apr 60 |                                     |                   |           |            | 0.46            | 0.99     | 0.15     | 0.19                  |        |      |       |  |
|                          | IV 9-1.5         |                         | 3 May 60  |                                     |                   |           |            | 0.46            | 1.04     | 0.37     | 0.50                  |        |      |       |  |
|                          | IV 10-1.5        |                         | 13 May 60 |                                     |                   |           |            | 0.46            | 1.10     | 0.24     | 0.37                  |        |      |       |  |
|                          | I E              |                         | 25 Nov 59 |                                     |                   |           |            | 0.61            | 1.14     | 0.15     | 0.31                  |        |      |       |  |
|                          | P 2A             |                         | 12 Nov 59 |                                     |                   |           |            | 0.61            | 1.11     | 0.34     | 0.48                  |        |      |       |  |
|                          | P 2B             |                         | 23 Nov 59 |                                     |                   |           |            | 0.61            | 1.08     | 0.21     | 0.34                  |        |      |       |  |
|                          | P 2C             |                         | 5 Apr 60  |                                     |                   |           |            | 0.61            | 1.19     | 0.55     | 1.14                  |        |      |       |  |
|                          | P 8A             |                         | 18 Nov 59 |                                     |                   |           |            | 0.61            | 1.05     | 0.43     | 0.54                  |        |      |       |  |
|                          | IV 1-2.0         |                         | 11 Apr 60 |                                     |                   |           |            | 0.61            | 1.02     | 0.15     | 0.22                  |        |      |       |  |
|                          | IV 2-2.0         |                         | 15 Apr 60 |                                     |                   |           |            | 0.61            | 1.17     | 0.21     | 0.41                  |        |      |       |  |
|                          | IV 3-2.0         |                         | 18 Apr 60 |                                     |                   |           |            | 0.61            | 1.16     | 0.18     | 0.36                  |        |      |       |  |
|                          | IV 4-2.0         |                         | 20 Apr 60 |                                     |                   |           |            | 0.61            | 0.99     | 0.18     | 0.27                  |        |      |       |  |
|                          | IV 5-2.0         |                         | 21 Apr 60 |                                     |                   |           |            | 0.61            | 1.18     | 0.24     | 0.51                  |        |      |       |  |
|                          | IV 6-2.0         |                         | 26 Apr 60 |                                     |                   |           |            | 0.61            | 1.13     | 0.49     | 0.81                  |        |      |       |  |
|                          | IV 7-2.0         |                         | 27 Apr 60 |                                     |                   |           |            | 0.61            | 1.07     | 0.43     | 0.65                  |        |      |       |  |
|                          | IV 8-2.0         |                         | 2 May 60  |                                     |                   |           |            | 0.61            | 1.05     | 0.37     | 0.57                  |        |      |       |  |
|                          | IV 9-2.0         |                         | 3 May 60  |                                     |                   |           |            | 0.61            | 1.20     | 0.21     | 0.83                  |        |      |       |  |
|                          | IV 10-2.0        |                         | 12 May 60 |                                     |                   |           |            | 0.61            | 1.16     | 0.30     | 0.56                  |        |      |       |  |
|                          | I F              |                         | 18 Feb 60 |                                     |                   |           |            | 0.76            | 1.23     | 0.52     | 0.99                  |        |      |       |  |
|                          | IV 1-1.2         |                         | 14 Apr 60 |                                     |                   |           |            | 0.76            | 1.05     | 0.30     | 0.37                  |        |      |       |  |
|                          | IV 2-2.5         |                         | 15 Apr 60 |                                     |                   |           |            | 0.76            | 1.13     | 0.30     | 0.54                  |        |      |       |  |
|                          | IV 3-2.5         |                         | 19 Apr 60 |                                     |                   |           |            | 0.76            | 1.17     | 0.18     | 0.37                  |        |      |       |  |
|                          | IV 4-2.5         |                         | 20 Apr 60 |                                     |                   |           |            | 0.76            | 1.21     | 0.27     | 0.58                  |        |      |       |  |
|                          | IV 5-2.5         |                         | 25 Apr 60 |                                     |                   |           |            | 0.76            | 1.19     | 0.61     | 1.08                  |        |      |       |  |
|                          | IV 6-2.5         |                         | 26 Apr 60 |                                     |                   |           |            | 0.76            | 1.10     | 0.37     | 1.57                  |        |      |       |  |
|                          | IV 7-2.5         |                         | 28 Apr 60 |                                     |                   |           |            | 0.76            | 1.14     | 0.49     | 1.00                  |        |      |       |  |
|                          | IV 8-2.5         |                         | 2 May 60  |                                     |                   |           |            | 0.76            | 1.14     | 0.61     | 1.09                  |        |      |       |  |
|                          | IV 9-2.5         |                         | 12 May 60 |                                     |                   |           |            | 0.76            | 1.23     | 0.30     | 0.65                  |        |      |       |  |
|                          | IV 10-2.5        |                         | 13 May 60 |                                     |                   |           |            | 0.76            | 1.10     | 0.43     | 0.62                  |        |      |       |  |
|                          | P 3-A            |                         | 9 Nov 59  |                                     |                   |           |            | 0.91            | 0.84     | 0.15     | 0.13                  |        |      |       |  |
|                          | P 3-B            |                         | 26 Jan 60 |                                     |                   |           |            | 0.91            | 1.21     | 0.67     | 1.50                  |        |      |       |  |
|                          | P 4-A            |                         | 7 Dec 59  |                                     |                   |           |            | 1.22            | 1.08     | 0.12     | 0.25                  |        |      |       |  |
|                          | P 4-B*           |                         | 27 Jan 60 |                                     |                   |           |            | 1.22            | 1.37     | 0.67     | 1.88                  |        |      |       |  |
|                          | IV 4-3.0         |                         | 28 Jul 60 |                                     |                   |           |            | 0.91            | 1.23     | 0.12     | 0.53                  |        |      |       |  |
|                          | IV 5-3.0         |                         | 28 Jul 60 |                                     |                   |           |            | 0.91            | 1.23     | 0.12     | 0.73                  |        |      |       |  |
|                          | IV 6-3.0         |                         | 29 Jul 60 |                                     |                   |           |            | 0.91            | 1.16     | 0.37     | 0.62                  |        |      |       |  |
|                          | IV 1-4.0         |                         | 21 Jun 60 |                                     |                   |           |            | 1.22            |          |          |                       |        |      |       |  |
|                          | IV 2-4.0         |                         | 22 Jun 60 |                                     |                   |           |            | 1.22            | 1.01     | 0.12     | 0.18                  |        |      |       |  |
|                          | IV 3-4.0         |                         | 23 Jun 60 |                                     |                   |           |            | 1.22            |          |          |                       |        |      |       |  |
|                          | III 0.5          |                         | 8 Jun 60  |                                     |                   |           |            | 256             | 116.10   | 0.97     | 3.08                  |        | 1.37 | 18.21 |  |
|                          | III 0.75         |                         | 17 Jun 60 |                                     |                   |           |            |                 |          | 1.45     | 3.26                  |        | 2.13 | 25.85 |  |
|                          | III 1.00         |                         | 13 Jun 60 |                                     |                   |           |            |                 |          | 1.94     | 3.38                  |        | 1.68 | 27.84 |  |
| III 1.25                 | 19 Jun 60        |                         |           | 2.42                                | 3.57              | 1.74      | 34.26      |                 |          |          |                       |        |      |       |  |
| G2-34                    | 16 Jul 62        |                         |           | 2.42                                | 3.57              | 1.55      | 25.60      |                 |          |          |                       |        |      |       |  |
| III 1.50                 | 15 Jun 60        |                         |           | 2.90                                | 3.86              | 1.07      | 23.33      |                 |          |          |                       |        |      |       |  |
| G2-35                    | 18 Jul 62        |                         |           | 2.90                                | 3.63              | 1.49      | 33.19      |                 |          |          |                       |        |      |       |  |
| III 2.0a                 | 26 Jul 60        |                         |           | 3.87                                | 3.54              | 0.85      | 15.57      |                 |          |          |                       |        |      |       |  |
| III 2.0b                 | 22 Aug 60        |                         |           | 3.87                                | 3.63              | 0.79      | 12.40      |                 |          |          |                       |        |      |       |  |
| III 1.25b                | 8 Aug 60         |                         |           | 2.42                                | 3.47              | 1.58      | 32.25      |                 |          |          |                       |        |      |       |  |
| Unnamed                  | --*              | Sandia Laboratories     | 1960      | Alluvium                            | TNT               | 5,000     | 2,268.00   | 0.00            | 5.64     | 1.45     | 83.53                 | 30     |      |       |  |
| Stagecoach               | 1                | Sandia Laboratories     | 15 Mar 60 | Alluvium (Nevada Test Site Area 10) | TNT               | 40,120    | 18,198.10  | 24.38           | 17.37    | 2.41     | 1,391.63              | 20     |      |       |  |
|                          | 2                |                         | 40,240    |                                     |                   | 18,252.60 | 5.21       | 15.39           | 7.19     | 2,368.70 |                       |        |      |       |  |
|                          | 3                |                         | 40,070    |                                     |                   | 18,175.40 | 10.42      | 17.86           | 8.90     | 4,094.62 |                       |        |      |       |  |
| Scooter                  | --               | Sandia Laboratories     | 13 Oct 60 | Alluvium (Nevada Test Site Area 10) | TNT               | 987,410   | 447,881.70 | 38.10           | 46.88    | 22.71    | 74,813.11             | 21     |      |       |  |
| Rowboat                  | 7a*              | LRL                     | 26 Jun 61 | ?                                   | TNT               | 278       | 126.10     | 4.54            | 6.74     | 0.88     | --                    | 37     |      |       |  |
|                          | 8a*              |                         | 28 Jun 61 |                                     |                   | 278       | 126.10     | 4.54            | 8.75     | 0.75     | --                    |        |      |       |  |
| Pre-Buggy II             | F-1*             | Nuclear Cratering Group | 6 Aug 63  | Alluvium (Nevada Test Site Area 5)  | Nitro-methane     | 1,000     | 453.60     | 6.04            | 6.92     | 3.60     | 222.57                | 22     |      |       |  |
|                          | F-2*             |                         | 6 Aug 63  |                                     |                   | 1,000     | 453.60     | 6.04            | 6.46     | 3.60     | 170.75                |        |      |       |  |
|                          | F-3              |                         | 6 Aug 63  |                                     |                   | 950       | 430.91     | 5.64            | 6.43     | 3.35     | 196.80                |        |      |       |  |
|                          | F-4              |                         | 6 Aug 63  |                                     |                   | 950       | 430.91     | 5.59            | 6.74     | 3.29     | 214.08                |        |      |       |  |
| Unnamed series           | G2-60            | Sandia Laboratories     | 19 Nov 63 | Alluvium (Albuquerque)              | TNT               | 64        | 29.00      | 2.13            | 2.10     | 0.62     | 4.90                  | 28     |      |       |  |
|                          | G2-62            |                         | 26 Nov 63 |                                     |                   | 64        | 29.00      | 2.13            | 2.26     | 0.62     | 5.15                  |        |      |       |  |
|                          | G2-64            |                         | 2 Dec 63  |                                     |                   | 64        | 29.00      | 2.13            | 2.10     | 0.62     | 4.59                  |        |      |       |  |
| Air Vent                 | III 1A           | Sandia Laboratories     | 31 Jan 64 | Playa (Frenchman Flat)              | TNT               | 64        | 29.03      | 0.00            | 1.04     | 0.48     | 0.68                  | 31     |      |       |  |
|                          | III 1B           |                         | 31 Jan 64 |                                     |                   | 64        | 29.03      | 0.00            | 1.04     | 0.55     | 0.74                  |        |      |       |  |
|                          | III 1C           |                         | 31 Jan 64 |                                     |                   | 64        | 29.03      | 0.00            | 0.99     | 0.55     | 0.65                  |        |      |       |  |
|                          | III 1D           |                         | 31 Jan 64 |                                     |                   | 64        | 29.03      | 0.00            | 1.07     | 0.57     | 0.80                  |        |      |       |  |
|                          | III 2A           |                         | 11 Jan 64 |                                     |                   | 1,000     | 453.60     | 0.00            | 2.85     | 1.30     | 12.52                 |        |      |       |  |
|                          | III 2B           |                         | 11 Jan 64 |                                     |                   | 1,000     | 453.60     | 0.00            | 3.08     | 1.39     | 14.64                 |        |      |       |  |
|                          | III 2C           |                         | 13 Jan 64 |                                     |                   | 1,000     | 453.60     | 0.00            | 2.72     | 1.30     | 12.46                 |        |      |       |  |
|                          | III 3A           |                         | 8 Jan 64  |                                     |                   | 6,000     | 2,721.60   | 0.00            | 5.01     | 2.00     | 71.36                 |        |      |       |  |
|                          | III 3B           |                         | 9 Jan 64  |                                     |                   | 6,000     | 2,721.60   | 0.00            | 5.34     | 2.11     | 76.54                 |        |      |       |  |
| Flat Top                 | II               | Sandia Laboratories     | 17 Feb 64 | Playa (Frenchman Flat)              | TNT               | 40,000    | 18,143.70  | 0.00            | 10.9     | 3.93     | 680.45                | 24     |      |       |  |
|                          | III              |                         | 17 Feb 64 |                                     |                   | 40,000    | 18,143.70  | 0.00            | 11.83    | 5.67     | 1,070.38              |        |      |       |  |

(Continued)

\* Data not used in the statistical analysis.

(Sheet 3 of 4)

Table B1 (Concluded)

| Series Name                                       | Shot Designation | Sponsor   | Date      | Medium   | Type of Explosive | Charge    |           | Apparent Crater |          |         |                       | Source |
|---|------------------|---|-----------|--|-------------------|-----------|-----------|-----------------|----------|---------|-----------------------|--------|
|   |                  |   |           |  |                   | Weight lb | Weight kg | Burial Depth m  | Radius m | Depth m | Volume m <sup>3</sup> |        |
| Air Vent  | I-1              | Defense Atomic Support Agency/Sandia Laboratories | 14 Dec 63 | Playa (Frenchman Flat) (Nevada Test Site Area 5) | TNT               | 40,000    | 18,143.70 | 5.24            | 14.51    | 6.85    | 2,052.97              | 31     |
|   | II-1*            |   | 30 Jan 64 |  |                   | 256       | 116.12    | -0.26           | 0.98     | 0.25    | 0.37                  |        |
|   | II-2A            | 30 Jan 64   |           |  |                   | 0.00      | 1.69      | 0.73            | 2.70     |         |                       |        |
|   | II-2B            | 29 Jan 64   |           |  |                   | 0.00      | 1.65      | 0.74            | 2.64     |         |                       |        |
|   | II-3             | 29 Jan 64   |           |  |                   | 0.26      | 2.05      | 1.03            | 6.67     |         |                       |        |
|   | II-4             | 29 Jan 64   |           |  |                   | 0.48      | 2.32      | 1.13            | 6.99     |         |                       |        |
|   | II-5A            | 28 Jan 64   |           |  |                   | 0.97      | 2.69      | 1.26            | 12.06    |         |                       |        |
|   | II-5B            | 28 Jan 64   |           |  |                   | 0.97      | 2.59      | 1.33            | 10.79    |         |                       |        |
|   | II-6             | 28 Jan 64   |           |  |                   | 1.45      | 2.92      | 1.41            | 14.64    |         |                       |        |
|   | II-7A            | 27 Jan 64   |           |  |                   | 1.94      | 2.99      | 1.33            | 14.32    |         |                       |        |
|   | II-7B            | 27 Jan 64   |           |  |                   | 1.94      | 3.03      | 1.37            | 15.40    |         |                       |        |
|   | II-8             | 27 Jan 64   |           |  |                   | 2.42      | 3.15      | 1.21            | 13.68    |         |                       |        |
|   | II-9A            | 24 Jan 64   |           |  |                   | 2.90      | 3.35      | 1.11            | 13.76    |         |                       |        |
|   | II-9B            | 23 Jan 64   |           |  |                   | 2.90      | 3.36      | 0.71            | 9.40     |         |                       |        |
|   | II-10A*          | 24 Jan 64   |           |  |                   | 3.87      | 6.98      | -1.16           | -33.36   |         |                       |        |
|   | II-10B*          | 23 Jan 64   |           |  |                   | 3.87      | 8.05      | -1.26           | -70.79   |         |                       |        |
|   | II-11A*          | 16 Jan 64   |           |  |                   | 4.85      | 6.89      | -1.25           | -75.83   |         |                       |        |
| II-11B*   | 16 Jan 64        |   | 4.85      | 6.80   | -1.34             | -77.08    |           |                 |          |         |                       |        |
| II-12*  | 17 Jan 64        |   | 5.81      | 6.71   | -0.81             | -53.18    |           |                 |          |         |                       |        |
| II-13*  | 17 Jan 64        |   | 6.77      | 7.13   | -0.41             | -28.40    |           |                 |          |         |                       |        |
| II-14*  | 17 Jan 64        |   | 7.74      | 7.53   | -0.19             | -25.49    |           |                 |          |         |                       |        |
| Pre Capsa   | 1-1              | Sandia Laboratories                               | 3 May 65  | Alluvium (Albuquerque)                           | TNT               | 256       | 116.10    | 2.90            | 4.10     | 2.13    | 53.94                 | 29     |
|   | 2-1              |   | 6 Jun 65  |  |                   | 256       | 116.10    | 2.90            | 3.91     | 2.05    | 50.49                 |        |
| Calibration Shots of Row Craters (unnamed series) | C 2              | Sandia Laboratories                               | 14 Jun 66 | Alluvium (Albuquerque)                           | TNT               | 64        | 29.03     | 1.83            | 2.43     | 1.20    | 12.03                 | 26     |
|   | C 3              |   | 14 Jun 66 |  |                   | 64        | 29.03     | 1.83            | 2.51     | 1.35    | 14.27                 |        |
|   | 1                |   | 1 Jun 66  |  |                   | 64        | 29.03     | 1.83            | 2.49     | 1.31    | 12.86                 |        |
| Calibration Shots of Row Craters (unnamed series) | 6-1              | Sandia Laboratories                               | 7 Oct 66  | Alluvium   | TNT               | 64        | 29.03     | 1.83            | 1.20     | 1.20    | 10.02                 | 27     |
|   | 7-1              |   | 11 Oct 66 |  |                   | 2.13      | 2.35      | 0.98            | 9.00     |         |                       |        |
|   | 8-1              |   | 18 Oct 66 |  |                   | 2.13      | 2.55      | 1.21            | 14.53    |         |                       |        |
|   | 9-1              |   | 21 Oct 66 |  |                   | 1.83      | 2.56      | 1.30            | 11.64    |         |                       |        |
|   | 10-1             |   | 25 Oct 66 |  |                   | 1.83      | 2.43      | 1.49            | 11.47    |         |                       |        |
| Capsa   | 1                | Sandia Laboratories                               | 16 Aug 66 | Alluvium (Albuquerque)                           | TNT               | 1,000     | 453.60    | 4.57            | 5.74     | 2.16    | 114.54                | 30     |
|   | 2                |   | 18 Aug 66 |  |                   | 3.81      | 5.52      | 3.13            | 137.05   |         |                       |        |
|   | 3                |   | 24 Aug 66 |  |                   | 3.05      | 5.45      | 3.20            | 129.04   |         |                       |        |
|   | 4                |   | 26 Aug 66 |  |                   | 5.33      | 5.84      | 2.15            | 111.29   |         |                       |        |
|   | 5                |   | 31 Aug 66 |  |                   | 4.57      | 6.00      | 2.16            | 118.14   |         |                       |        |
|   | 6                |   | 2 Sep 66  |  |                   | 5.33      | 6.01      | 3.22            | 168.09   |         |                       |        |
|   | 7                |   | 13 Sep 66 |  |                   | 3.05      | 4.91      | 2.78            | 103.67   |         |                       |        |
|   | 8                |   | 16 Sep 66 |  |                   | 3.81      | 5.92      | 3.24            | 163.70   |         |                       |        |
|   | 9                |   | 21 May 68 |  |                   | 3.81      | 5.62      | 3.18            | 151.18   |         |                       |        |
|   | 10*              |   | 29 May 68 |  |                   | 3.81      | 5.91      | 3.45            | 183.21   |         |                       |        |
|   | 11*              |   | 13 Jun 68 |  |                   | 30,478    | 13,824.60 | 14.60           | 17.38    | 8.76    | 3,447.46              |        |
|   | 12*              |   | 25 Jul 68 |  |                   | 977       | 443.20    | 3.81            | 6.06     | 2.88    | 162.45                |        |
|   | 13*              |   | 25 Jul 68 |  |                   | 981       | 445.00    | 4.57            | 5.89     | 2.94    | 146.74                |        |
| TTR-211   | 40               | Sandia Laboratories                               | 11 Aug 66 | Playa (Test Range)                               | TNT               | 64        | 29.03     | 1.22            | 2.22     | 1.27    | 7.36                  | 32     |
|   | 47               |   | 18 May 67 |  |                   | 64        | 29.03     | 1.52            | 2.43     | 1.16    | 9.23                  |        |
|   | 48               |   | 24 May 67 |  |                   | 64        | 29.03     | 1.83            | 2.56     | 1.27    | 10.45                 |        |
|   | 49               |   | 8 Jun 67  |  |                   | 64        | 29.03     | 2.13            | 2.34     | 0.92    | 5.83                  |        |
|   |                  |   |           |  |                   |           |           |                 |          |         |                       |        |
| TTR 211   | 51               | Sandia Laboratories                               | 7 Jul 67  | Playa (Tonopah Test Range)                       | TNT               | 64        | 29.03     | 0.00            | 1.10     | 0.47    | 0.73                  | 32     |
|   | 52               |   | 10 Aug 67 |  |                   | 1,000     | 453.60    | 0.00            | 2.86     | 1.26    | 11.30                 |        |
|   | 53               |   | 9 Jan 68  |  |                   | 64        | 29.03     | 0.00            | 0.98     | 0.45    | 0.57                  |        |
|   | 54*              |   | 19 Jan 68 |  |                   | 8         | 3.63      | 0.91            | 1.11     | 0.30    | 0.46                  |        |
|   | 55               |   | 21 Mar 68 |  |                   | 256       | 116.12    | 2.90            | 3.63     | 1.48    | 25.68                 |        |
|   | 56               |   | 20 Apr 68 |  |                   | 1,000     | 453.60    | 0.00            | 3.01     | 1.46    | 16.79                 |        |
|   | 42               |   | 25 Oct 66 |  |                   | 64        | 29.03     | 2.10            | 2.23     | 0.89    | 5.52                  |        |

\* Data not used in the statistical analysis.

APPENDIX C: DITCH DIMENSIONS FROM HIGH-EXPLOSIVE  
ROW-CHARGE DETONATIONS IN ROCK AND SOIL

Table C1

## Ditch Dimensions from High-Explosive Row-Charge Detonations in Rock and Soil

| Series Name  | Shot Designation | Sponsor             | Date        | Medium                                | Type of Explosive                             | Charge        |                 | Depth of Burial | Spacing Between Charges | Average Apparent Crater |         |                       | Saddle   |          | Source |
|--------------|------------------|---------------------|-------------|---------------------------------------|---|---------------|-----------------|-----------------|-------------------------|-------------------------|---------|-----------------------|----------|----------|--------|
|              |                  |                     |             |                                       |   | Weight lb     | Weight kg       |                 |                         | Width m                 | Depth m | Volume m <sup>3</sup> | Width at | Depth at |        |
| Toboggan     | A-1              | Sandia Laboratory   | Spring 1959 | Playa (Nevada Test Site - Yucca Lake) | TNT   | 6 each at 8   | 6 each at 3.63  | 0.61            | 0.91                    | 3.05                    | 0.62    | 5.07                  | --       | --       | 36     |
|              | B-2              |                     |             |                                       |   | 6 each at 8   | 6 each at 3.63  | 0.61            | 1.07                    | 2.16                    | 0.61    | 5.30                  | --       | --       |        |
|              | C-3              |                     |             |                                       |   | 6 each at 8   | 6 each at 3.63  | 0.61            | 1.22                    | 2.13                    | 0.50    | 4.54                  | --       | --       |        |
|              | D-4              |                     |             |                                       |   | 6 each at 256 | 6 each at 116.1 | 1.93            | 3.87                    | 7.01                    | 1.59    | 155.94                | --       | --       |        |
|              | E-5              |                     |             |                                       |   | 6 each at 8   | 6 each at 3.63  | 0.61            | 1.52                    | 1.77                    | 0.62    | 4.33                  | --       | --       |        |
|              | F-6              |                     |             |                                       |   | 6 each at 8   | 6 each at 3.63  | 0.61            | 1.83                    | 1.98                    | 0.43    | One charge misfired   | --       | --       |        |
| Little Ditch | II A-2           | Sandia Laboratories | 17 May 60   | Alluvium (Albuquerque)                | TNT   | 7 each at 8   | 7 each at 3.63  | 0.30            | 0.61                    | 1.31                    | 0.22    | 0.68                  | 1.00     | 0.62     | 25     |
|              | II C-1.5         |                     | 22 Jun 59   |                                       | 0.00  | 0.46          | 2.01            | 0.49            | 1.92                    | 1.00                    | 0.97    |                       |          |          |        |
|              | II C-2.5         |                     | 16 Jul 59   |                                       | 0.30  | 0.30          | 2.71            | 0.49            | 2.71                    | 1.00                    | 0.90    |                       |          |          |        |
|              | II C-3           |                     | 01 Sep 59   |                                       | 0.30  | 0.30          | 0.91            | 0.33            | 1.89                    | 1.00                    | 0.94    |                       |          |          |        |
|              | II C-4           |                     | 14 Oct 59   |                                       | 0.30  | 0.30          | 1.52            | 0.33            | 1.89                    | 1.00                    | 0.94    |                       |          |          |        |
|              | II C-5           |                     | 05 Oct 59   |                                       | 0.30  | 0.30          | 1.22            | 1.68            | 0.37                    | 2.78                    | 1.04    | 0.60                  |          |          |        |
|              | II C-5B          |                     | 24 Sep 59   |                                       | 0.30  | 0.30          | 1.52            | 1.37            | 0.24                    | 1.81                    | 0.69    | 0.60                  |          |          |        |
|              | II C-7           |                     | 16 Oct 59   |                                       | 0.30  | 0.30          | 1.22            | 1.29            | 0.21                    | 1.68                    | 0.48    | 0.40                  |          |          |        |
|              | II D-3           |                     | 10 Nov 59   |                                       | 0.46  | 0.46          | 2.55            | 0.07            | 0.03                    | 2.55                    | 0.07    | 0.03                  |          |          |        |
|              | II D-3.5         |                     | 9 Mar 60    |                                       | 0.46  | 0.46          | 2.16            | 0.49            | 3.79                    | 1.00                    | 1.00    |                       |          |          |        |
|              | II E-3.0         |                     | 9 Dec 59    |                                       | 0.61  | 0.61          | 1.07            | 1.86            | 0.53                    | 3.89                    | 0.95    | 0.94                  |          |          |        |
|              | II E-4.0         |                     | 10 Mar 60   |                                       | 0.61  | 0.61          | 0.91            | 2.53            | 0.53                    | 5.44                    | 1.00    | 0.94                  |          |          |        |
|              | II E-5.0         |                     | 24 May 60   |                                       | 0.61  | 0.61          | 1.22            | 2.35            | 0.73                    | 7.61                    | 0.97    | 0.92                  |          |          |        |
|              | II E-7.0         |                     | 27 May 60   |                                       | 0.61  | 0.61          | 1.52            | 1.83            | 0.49                    | 5.23                    | 0.77    | 0.78                  |          |          |        |
|              | II F-3.5         |                     | 13 Nov 59   |                                       | 0.76  | 0.76          | 2.13            | 1.62            | 0.26                    | 3.65                    | 0.42    | 0.31                  |          |          |        |
|              | II F-4.0         |                     | 11 Mar 60   |                                       | 0.76  | 0.76          | 1.07            | 2.44            | 0.56                    | 5.77                    | 1.00    | 0.95                  |          |          |        |
|              | II F-4.5         |                     | 10 Mar 60   |                                       | 0.76  | 0.76          | 1.22            | 2.45            | 0.64                    | 7.39                    | 1.00    | 1.00                  |          |          |        |
|              | II G-3.0         |                     | 29 Jan 60   |                                       | 0.91  | 0.91          | 1.37            | 2.44            | 0.70                    | 9.37                    | 1.00    | 1.00                  |          |          |        |
|              | II G-3.5         |                     | 10 Nov 59   |                                       | 0.91  | 0.91          | 1.07            | 2.84            | 0.73                    | 6.79                    | 1.00    | 1.00                  |          |          |        |
|              | II G-4.0A        |                     | 11 Dec 59   |                                       | 0.91  | 0.91          | 1.07            | 2.71            | 0.55                    | 6.34                    | 1.00    | 1.00                  |          |          |        |
|              | II G-4.0C        |                     | 16 Feb 60   |                                       | 0.91  | 0.91          | 1.22            | 2.47            | 0.37                    | 4.69                    | 0.98    | 1.00                  |          |          |        |
|              | II G-4.0B        |                     | 4 Apr 60    |                                       | 0.91  | 0.91          | 1.22            | 2.75            | 0.79                    | 9.48                    | 1.00    | 1.00                  |          |          |        |
|              | II G-4.5         |                     | 19 Feb 60   |                                       | 0.91  | 0.91          | 1.22            | 2.89            | 0.85                    | 10.81                   | 1.00    | 1.00                  |          |          |        |
|              | II G-6.0         |                     | 25 Feb 60   |                                       | 0.91  | 0.91          | 1.37            | 2.58            | 0.78                    | 10.56                   | 1.00    | 0.96                  |          |          |        |
|              | II G-8.0         |                     | 4 Mar 60    |                                       | 0.91  | 0.91          | 1.83            | 2.58            | 0.73                    | 10.75                   | 1.00    | 0.92                  |          |          |        |
| II G-9.0     | 9 Mar 60         | 0.91                | 0.91        | 2.44                                  | 2.34  | 0.59          | 10.18           | 0.90            | 0.86                    |                         |         |                       |          |          |        |
| II H-4.0     | 25 May 60        | 0.91                | 0.91        | 2.74                                  | 1.94  | 0.37          | 7.45            | 0.40            | 0.41                    |                         |         |                       |          |          |        |
| II H-4.0     | 28 Mar 60        | 0.91                | 0.91        | 1.07                                  | Same as II J; 7.0 with mounds between charges |               |                 |                 |                         |                         |         |                       |          |          |        |
| II J-3.5     | 3 Mar 60         | 1.22                | 1.22        | 2.92                                  | 0.64  | 8.10          | 1.00            | 1.10            | 1.10                    |                         |         |                       |          |          |        |
| II J-4.0     | 6 Apr 60         | 1.22                | 1.22        | 1.07                                  | 3.08  | 0.78          | 10.13           | 1.00            | 1.04                    |                         |         |                       |          |          |        |
| II J-5.0     | 2 Jun 60         | 1.22                | 1.22        | 1.22                                  | 3.03  | 0.42          | 6.93            | 1.02            | 1.21                    |                         |         |                       |          |          |        |
| II J-6.0     | 14 Mar 61        | 1.22                | 1.22        | 2.44                                  | 2.44  | 0.59          | 7.82            | 1.00            | 1.05                    |                         |         |                       |          |          |        |
| II J-7.0     | 20 May 60        | 1.22                | 1.22        | 1.56                                  | 1.56  | 0.15          | 3.81            | 0.81            | 1.11                    |                         |         |                       |          |          |        |
| II I-4.0     | 1 Jun 60         | 1.52                | 1.52        | 1.22                                  | 2.13  | 2.87          | 0.53            | 7.71            | 0.99                    | 1.06                    |         |                       |          |          |        |
| II I-4.0B    | 20 Mar 61        | 1.52                | 1.52        | 1.22                                  | 1.22  | 1.22          | 1.22            | 1.22            | 1.22                    | 1.22                    |         |                       |          |          |        |
| IV 14.3-9.52 | 17 Aug 60        | 2.90                | 2.90        | 4.36                                  | 8.78  | 1.98          | 372.31          | 1.00            | 1.00                    | 1.00                    |         |                       |          |          |        |
| V 15.87-9.52 | 30 Dec 60        | 2.90                | 2.90        | 4.84                                  | 7.47  | 1.83          | 298.08          | 1.00            | 1.00                    | 1.00                    |         |                       |          |          |        |
| II K-3.5A    | 1 Mar 61         | 1.37                | 1.37        | 2.84                                  | 2.84  | 0.20          | 7.22            | 0.98            | 1.03                    |                         |         |                       |          |          |        |
| II K-3.5B    | 6 Mar 61         | 1.37                | 1.37        | 2.96                                  | 2.96  | 0.10          | 6.14            | 0.84            | 1.11                    |                         |         |                       |          |          |        |
| II K-4.0     | 9 Mar 61         | 1.37                | 1.37        | 2.59                                  | 2.59  | 0.32          | 7.34            | 0.97            | 1.02                    |                         |         |                       |          |          |        |

(Continued)



## APPENDIX D: NOTATION

## Crater and Ditch Dimensions (All in Metres)

|                |   |
|----------------|---|
| B              | Charge burial depth   |
| D              | Maximum apparent depth of single crater                       |
| D <sub>r</sub> | Maximum apparent depth of row crater                          |
| L              | Ditch length from first to last charge location               |
| R              | Average apparent radius of single crater                      |
| R <sub>r</sub> | Average apparent half-width of row crater at charge locations |
| S              | Spacing between charges in a row shot                         |
| x              | Generalized linear crater dimension                           |

## Other Crater and Ditch Design Parameters

|                |  |
|----------------|--|
| a              | Reciprocal of scaling exponent   |
| c <sub>b</sub> | Coefficient for charge burial depth, metres/kilogram <sup>1/a</sup>                    |
| c <sub>d</sub> | Coefficient for apparent depth of single crater, metres/kilogram <sup>1/a</sup>        |
| c <sub>r</sub> | Coefficient for apparent radius of single crater, metres/kilogram <sup>1/a</sup>       |
| c <sub>s</sub> | Coefficient for spacing between charges in a row shot, metres/kilogram <sup>1/a</sup>  |
| c <sub>v</sub> | Coefficient for apparent volume of single crater, cubic metres/kilogram <sup>3/a</sup> |
| c <sub>x</sub> | Coefficient for linear crater dimension, metres/kilogram <sup>1/a</sup>                |
| n              | Number of charges in a row shot  |
| w              | Single or individual charge weight, kilograms  |
| V              | Apparent volume of single crater, cubic metres   |

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