UCRL-13875

RDA-TR-2604-001

ESTIMATES OF CRATER DIMENSIONS FOR NEAR-SURFACE EXPLOSIONS OF NUCLEAR AND HIGH-EXPLOSIVE SOURCES

SEPTEMBER 1976

By:
Henry F. Cooper, Jr.

Sponsored By:
LAWRENCE LIVERMORE LABORATORY
University of California
P.O. Box 808
Livermore, California 94550

MASTER

P.O. 9441605

R & D ASSOCIATES
Post Office Box 9695
Marina del Rey,
California 90291

4640 ADMIRALTY WAY • MARINA DEL REY • TELEPHONE: (213) 822-1715

DISCLAIMER

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

Estimates of Crater Dimensions for Near-Surface Explosions of Nuclear and High-Explosive Sources

5. TYPE OF REPORT & PERIOD COVERED

Technical Report

6. PERFORMING ORG. REPORT NUMBER

RDA-TR-2604-001

7. AUTHOR(s)

Henry F. Cooper, Jr.

8. CONTRACT OR GRANT NUMBER(s)

UCAL Subcontract 9441605

9. PERFORMING ORGANIZATION NAME AND ADDRESS

R & D Associates
P. O. Box 9695
Marina del Rey, CA 90291

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

Lawrence Livermore Laboratory
University of California, P. O. Box 808
Livermore, California 94550

12. REPORT DATE

October 1976

13. NUMBER OF PAGES

53

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS (of this report)

Unclassified

15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Crater data from numerous high-explosive (HE) experiments and from fewer nuclear explosive (NE) tests are used to develop an empirically based procedure for predicting crater dimensions from nuclear explosions in various geologic media. The HE crater data are used to rank the cratering efficiency of various geologies. NE crater data from dry soil at the Nevada Test Site and from saturated coral at Eniwetok and Bikini atolls are used to relate NE and HE cratering efficiency. Crater shapes from explosive and impact craters are

19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

examined to provide a basis for estimating crater radius and depth in a given geology once the crater volume is known. Best estimates of the crater volume and dimensions are presented along with an estimated range of uncertainty.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

1. INTRODUCTION

The objective of this paper is to present a methodology and associated uncertainties for predicting the crater dimensions from near-surface nuclear explosions as a function of weapon yield, height-of-burst, and geologic medium.

1.1 BACKGROUND

Considerable effort has been and is being expended to calculate craters from first principles. Calculations for buried nuclear sources, low energy density nuclear sources and high-explosive sources have been reasonably successful in that they produce crater volumes* to within a factor of two or so of experimental observations. However, calculations for contact or surface bursts of modern weapons produce craters that differ significantly from estimates based on the Pacific Nuclear Test data and empirically developed prediction methods to account for geologic variations from the Pacific Atolls. Since modern nuclear weapons are different from the test devices detonated in the Pacific, the calculations may be correct. However, the physics for surface burst sources is much more complex than for buried nuclear and HE sources, and the calculations are not yet validated. Furthermore, since some of the nuclear sources in the Pacific were at least grossly comparable to modern weapons,** it seems more credible, for the present, to base estimates for cratering efficiency for surface bursts on generalizations from the experimental data rather than on calculations. However, it should be kept in mind that the craters from high yield modern weapons detonated on or slightly above the surface _may_ be much smaller than the empirical predictions.

---

*Herein, "crater volume" refers to the apparent crater volume.

**However, in _all_ cases, the presence of extraneous material around the Pacific sources may have perturbed the energy coupling.

Such a generalization of existing experimental data requires synthesis of information from rather diverse high-explosive and nuclear tests, a procedure often requiring subjective judgments.* This paper provides a more systematic basis for a methodology suggested several years ago [1], a variant of which was adopted by the new Air Force Design Manual [2]. We also incorporate data not included in these previous publications and attempt to quantify the uncertainties in predicted craters.

1.2 ACCURACY GOALS

The reproducibility of craters from a given explosive source configuration in a given geology can reasonably estimate the lower limit of uncertainty in our predictions of crater dimensions for a given explosion. Even if we understood the physics precisely, our lack of knowledge about the source and the geology would make predictive methods no more accurate than the reproducibility observed on apparently identical experiments. Furthermore, knowledge of the reproducibility is necessary to compare cratering data from different geologies. Unfortunately, the data base for various combinations of sources and geologies is inadequate to estimate this reproducibility in most cases--especially for nuclear explosions where there is at most a single data point for any given source, height-of-burst, and geologic configuration. Some guidance for estimating the reproducibility of nuclear sources is provided by high-explosive experiments.

For example, detonations of 256-lb spherical TNT sources in alluvium provide the most extensive field test data base for a single explosive source in a single geology [3]. As shown in Figure 1, the crater volume data for a given charge configuration would be expected to scatter by a factor of 2 to 3 near the

---

*For example, the absence of explicit data may lead us to assume that the crater volume from a given source in one kind of "hard" rock is the same (to the degree that the experimental results are reproducible) as the crater volume produced by the same explosive sources in a different "hard" rock.

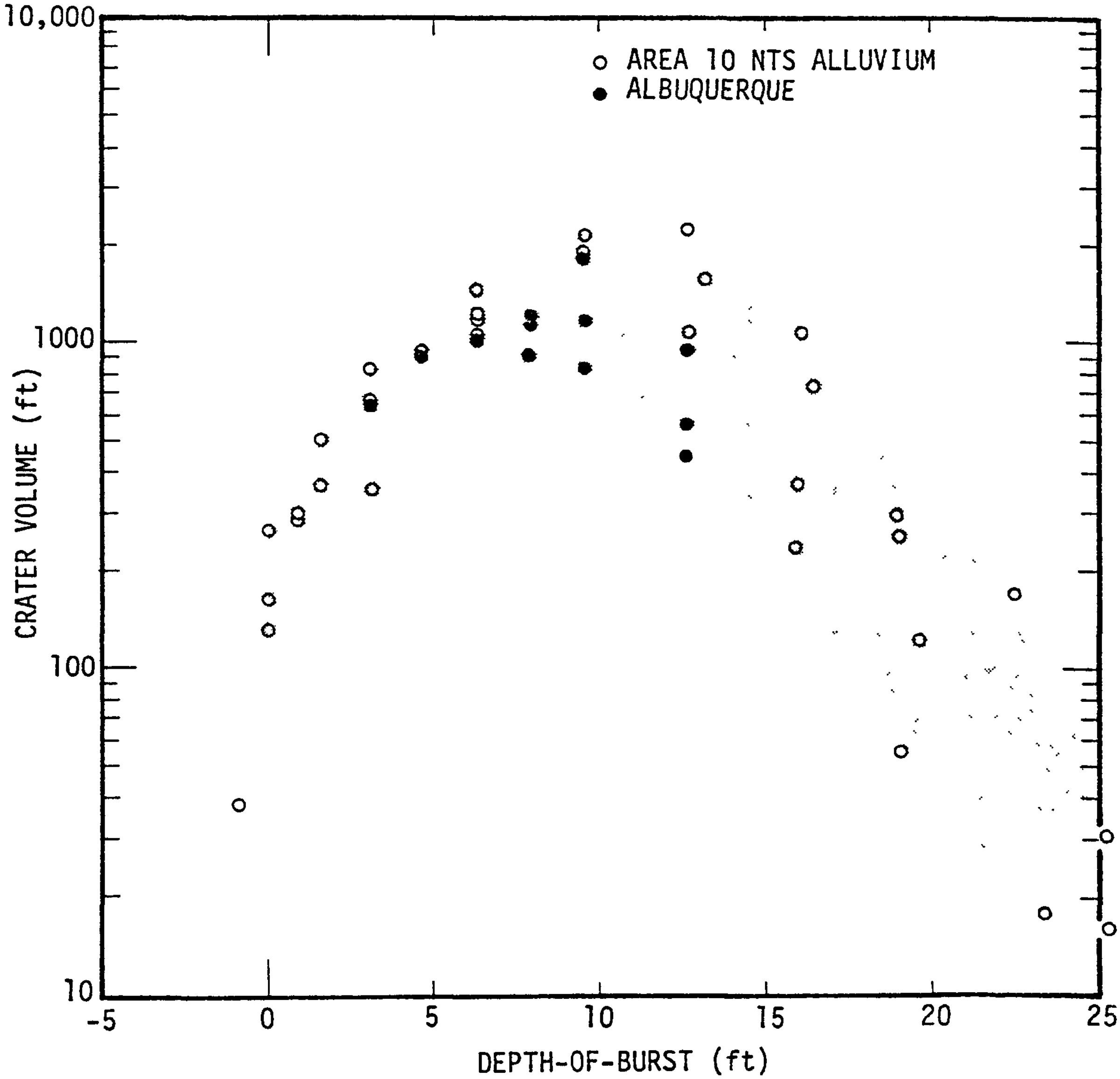

Figure 1. Crater Volume from 256-lb TNT Spherical Sources in Dry Alluvium

earth's surface and substantially more for depths greater than optimum depth-of-burst. Figure 2 illustrates the scatter in crater radius and depth data. Note that any possible systematic difference between cratering properties of Area 10 NTS alluvium and Albuquerque alluvium is less than the data scatter for either test area.

The scatter in these data may be associated with variations in source yield, charge placement, crater measurement techniques and geology.* It is estimated that the explosive yield of these charges was reproduced to within 5 percent; the variations in crater volume produced by variations in charge placement was probably less than 5 percent [5]; and the variations in linear dimensions introduced by post-test measurement error were probably less than 5 percent. Thus, the major portion of the data scatter is assumed to be associated with geologic variations in the vicinity of the source.

Figures 3 and 4 compare the more limited data base for 256-lb TNT sources in several other geologies with the alluvium data [3]. The main systematic variation from the alluvium data results from the tests in wet sand and moist clay. The reduced strength of these materials led to craters with 3 to 10 times the volume of craters in dry soils where intergranular friction opposes the late-time crater growth. The crater volumes, depths and radii from near-surface explosions in playa, dry clay and tuff cannot be clearly distinguished from the alluvium data. This result illustrates the strong influence of water on cratering efficiency, a fact also demonstrated by calculations of craters from deeply buried explosions [6].

It might be argued that small geologic inhomogeneities produce exaggerated effects for such small charges, and that larger yield

---

*Highly controlled laboratory test conditions can reduce the crater volume deviations to 10 percent or less [4]. However, the discussion presented here is based on data from field experiments where the control of source details and geology is much more difficult.

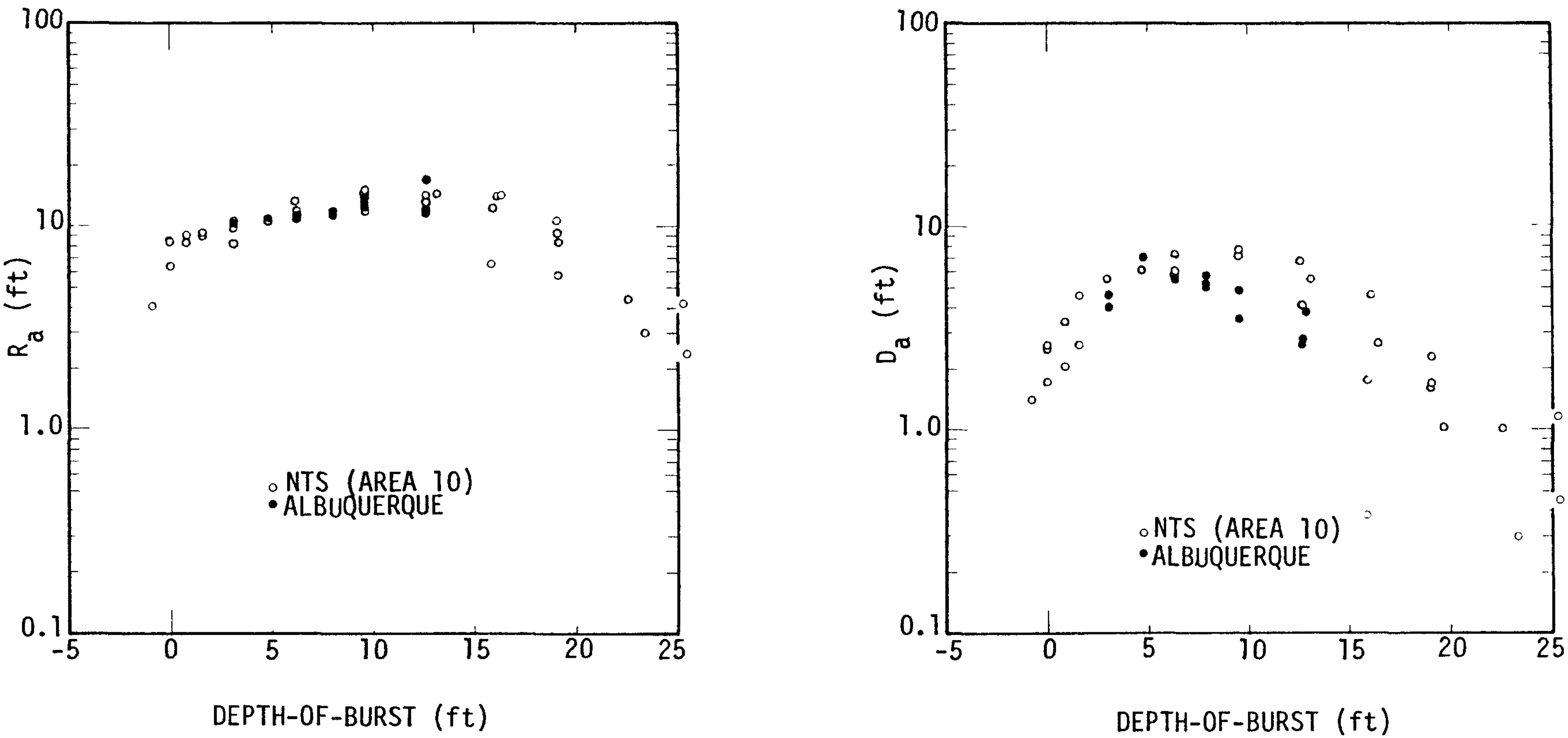

Figure 2. Crater Radius Depth from 256-lb TNT Spherical Sources in Dry Alluvium

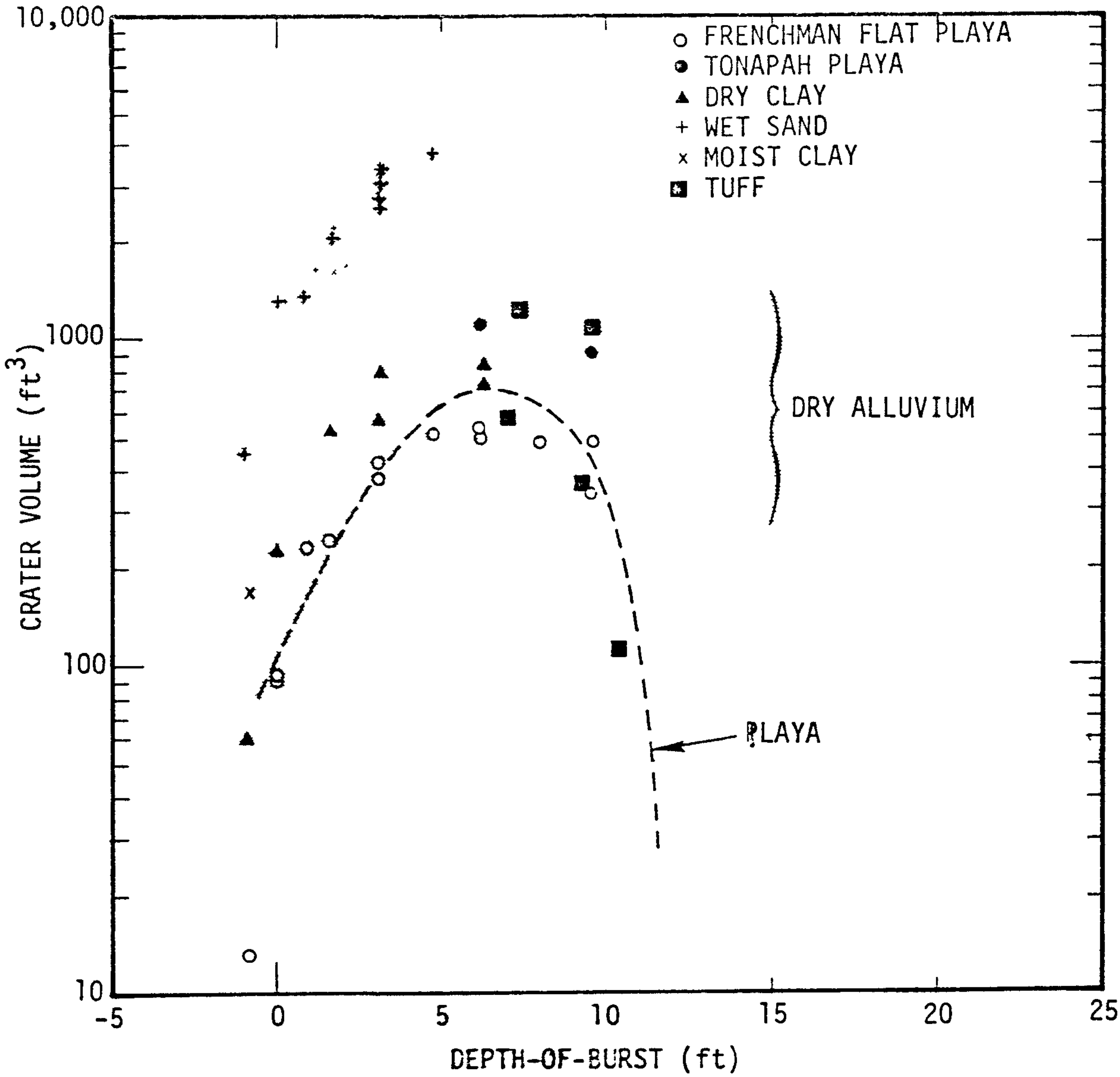

Figure 3. Crater Volume from 256 lb TNT Charges

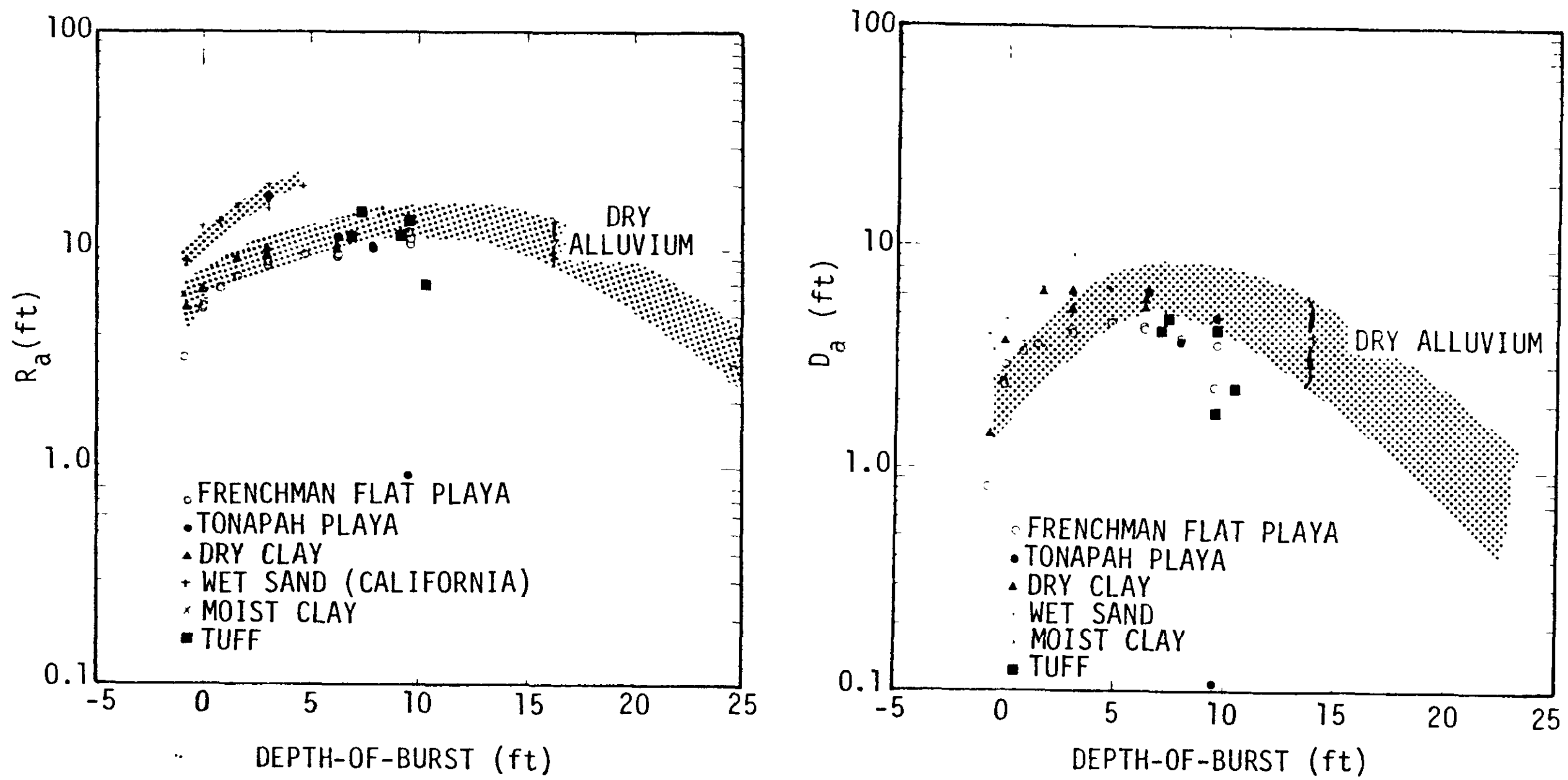

Figure 4. Crater Radius Depth from 256-lb TNT Spherical Sources in Dry Alluvium

explosions (nuclear or high-explosive sources) would produce less data scatter. However, it must be remembered that the scale of inhomogeneities that affects the cratering phenomena also changes with the explosive yield. While small inhomogeneities that are important for 256-lb TNT sources probably would not be important for large yield sources, other large inhomogeneities that would not be important for 256-lb sources may be important for substantially larger yields. Thus, it is not clear that the data scatter would significantly reduce with increasing yield. Unfortunately, little or no data exist to provide significant insight for larger yields. We shall assume that inhomogeneities in "generic" geologies could produce a factor of 2 variation in crater volume independent of weapon yield.

1.3 APPROACH

As indicated earlier, the most credible state-of-the-art procedures for predicting craters from near-surface nuclear explosions are empirically based. In simplest terms, these prediction procedures use the Pacific cratering data as a basis for estimating the cratering efficiency of modern weapons in saturated coral, and they use high-explosive and low energy density nuclear sources to establish an empirical link between the cratering efficiency of saturated Pacific coral and other geologic media.

The following section discusses the cratering efficiency prediction methodology and basic assumptions. Then Section 3 reviews the high-explosive and nuclear data base to provide the necessary functional relationships used in the methodology developed in Section 2. Section 4 then discusses the uncertainties in predicting crater dimensions once the crater volume is known. Finally, Section 5 summarizes the main points of the preceding sections.

2. METHODOLOGY FOR PREDICTING CRATER VOLUME FROM EXPLOSIVE SOURCES

This section develops and discusses a methodology for predicting crater volumes from near-surface explosions. Section 4 will indicate how crater radii and depths may be estimated once the crater volume is known.

Published high-explosive cratering data and the interpretation of nuclear cratering data [3,7] suggest that the apparent crater volume (V) from <u>surface bursts</u> in a given "uniform" medium* is approximately proportional to the yield (Y).** Thus, we assume that a near-surface burst at a height-of-burst h produces a crater volume

$$\bar{V} = V(G,\ S,\ H)Y \qquad (1)$$

where V(G, S, H) is the cratering efficiency, G and S are parameters characterizing the geology and source, and $H \equiv h/\bar{V}^{1/3}$ is the nondimensional height-of-burst defined to be consistent with a hypothesis that $\bar{V}^{1/3}$ is a fundamental characteristic length for correlating crater-induced ground motions [1].***

---

*The term "uniform" is used in a loose qualitative sense to refer to the case where no major discontinuity significantly influences crater formation. Although cratering phenomena affected by major geologic interfaces are beyond the scope of the present note, it is felt that the range of "uniform" geologies considered here will bracket the effects of such layering on cratering efficiency.

**The cratering efficiency for near optimum depth-of-burst explosions has been observed to vary as $Y^{0.882}$, presumably because of gravity effects [8]. Here we restrict our discussion to near-surface bursts where Equation 1 is expected to be valid. Modification of the methodology presented here is required to treat deeply buried bursts.

***The use of $H \equiv h/\bar{V}^{1/3}$ as a fundamental characteristic length can be considered to correspond to effective yield concepts applied previously to quantify the differences between

As will be illustrated in the following section, the HE cratering efficiency data from several different geologies suggest that geologic effects can be separated from height-of-burst effects when dimensions are scaled by $\bar{V}^{1/3}$. A natural generalization of that observation can be stated as

$$\bar{V}/Y = V(G, S, H) = V_o(G, S)F(S, H) \qquad (2)$$

where $V_o(S, G)$ is the cratering efficiency of source S in a "uniform" geology G at H = 0 and F(S, Y) is a height-of-burst shape factor for source S. Assuming that the generalization is valid, we define the relative cratering efficiency factor

$$K(G, S) \equiv \frac{V(G, S, H)}{V(G_o, S, H)} = \frac{V_o(G, S)}{V_o(G_o, S)} \qquad (3)$$

which relates the cratering efficiency in any "uniform) geology G to the cratering efficiency in a reference geology G_o. In subsequent discussion we shall take G_o as the Pacific coral where the large yield surface burst nuclear explosions occurred. In this case, $V_o(G_o, S)$ is the cratering efficiency derived for source S in Pacific coral.

<u>A fundamental assumption of the following discussion is that the relative cratering efficiency is a function of geology only, i.e., K(G, S) = K(G)</u>. Thus, we hypothesize that for "uniform" media

$$\bar{V}/Y = V(G, S, H) = K(G)V_o(G_o, S)F(S, H) \qquad (4)$$

---

the cratering efficiencies of low energy density and high energy density nuclear sources [9]. The use of crater-volume scaling at least partially accounts for variations in the cratering efficiency of whatever source considered, and to first order circumvents the requirement for a specific formulation relating the effective yield to the source design yield.

This assumption is most important because its consequence is that high-explosive cratering data can be used to determine the relative cratering efficiency of a given nuclear source in different geologic media. Some justification for this assumption is derived from examination of nuclear and high-explosive cratering data from the Pacific Proving Ground. Taking the reference geology G_o as Pacific coral, K (dry soil) was predicted several years ago [1] to be between 1/4 and 1/6 based on the cratering efficiency of low energy density nuclear sources at the Nevada Test Site and Eniwetok. (The data that served as the basis for this prediction are discussed in the following section.) As shown in Figure 5, the data from the more recent 1000-lb HE cratering experiments in the coral and Eniwetok fall within the uncertainty bars defined in the predictions based on $1/6 \leq K \text{ (alluvium)} \leq 1/4$ [10]. Because the ratio of cratering efficiency in dry soil to that in saturated coral appears to be approximately the same for both HE and low-energy density nuclear sources, we have some confidence in applying Equation 1 for high energy density nuclear sources thought to be more representative of modern weapons.*

The following section discusses the nuclear and high-explosive data base from which K(G), $V_o(G_o, S)$ and F(S, H) are estimated.

---

*It should be noted that the small craters were entirely in coral sand while the nuclear craters excavated consolidated coral as well as coral sand. Thus, large yield nuclear sources in the coral sand and coral sand/vuggy coral rock matrix must have equivalent cratering efficiencies for Equation 4 to be validated in a strict sense. It is credible that such would be the case, but it has not been demonstrated experimentally.

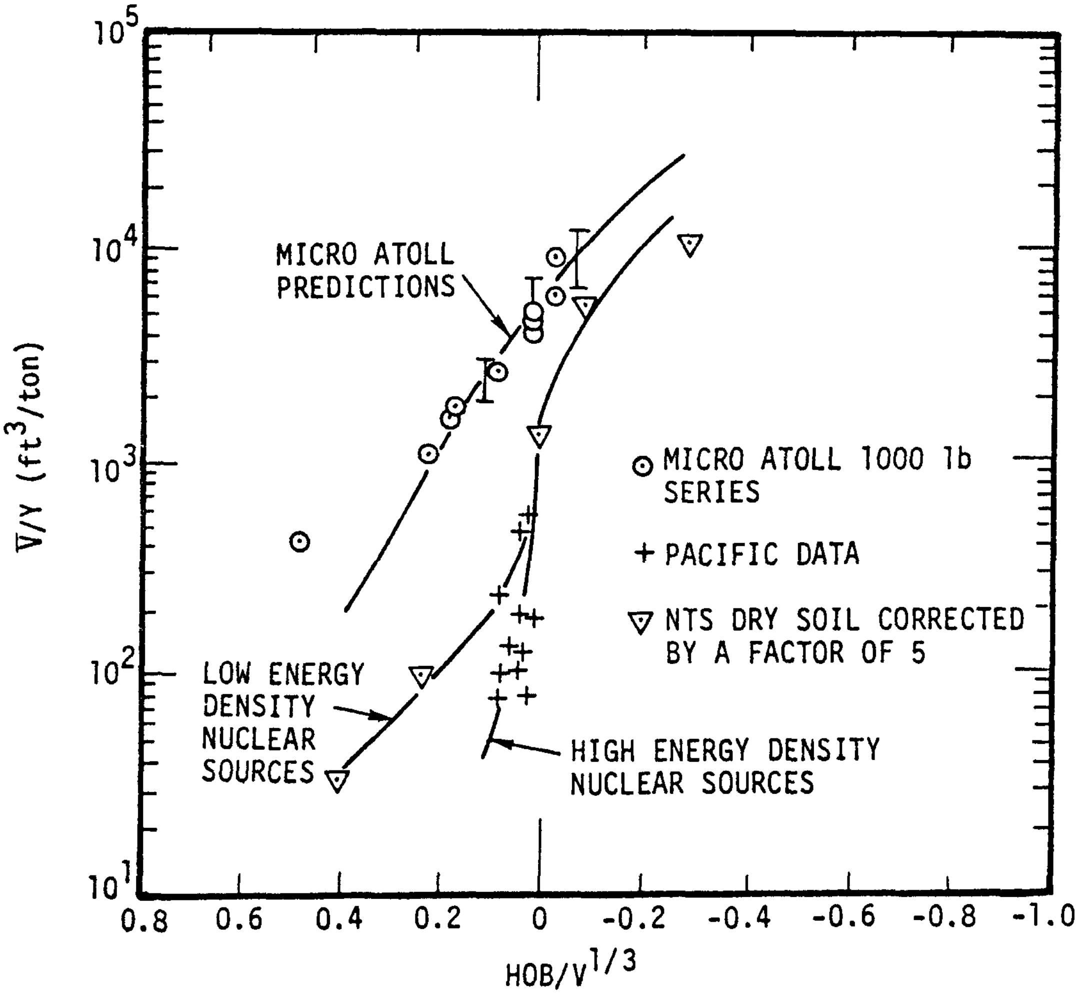

Figure 5. Comparison of MICRO ATOLL 1000-lb Cratering Efficiency with Prediction [1]

3. CRATERING EFFICIENCY FROM HIGH-EXPLOSIVE AND NUCLEAR EXPLOSIONS

This section summarizes the cratering efficiency data from high-explosive and nuclear tests. The high-explosive data are discussed first to illustrate certain trends suggested in the previous section, and to provide estimates for $V_o(G_o, HE)$, $F(HE, H)$ and $K(G)$. Then the nuclear data are examined to determine $V_o(G_o, NE)$ and $F(NE, H)$.

3.1 HIGH-EXPLOSIVE CRATERING EXPERIENCE

High-explosive cratering data exist for various heights-of-burst, for yields ranging from a few grams in laboratory experiments to 500 tons in field experiments, and for geologic materials that range from very incompetent saturated soil to dry hard rock. With very few exceptions inadequate data have been obtained to specify a complete height-of-burst curve for each geology and various explosive yields of interest.

The most extensive data base exists for 256-lb TNT spheres (Figures 1-4). Several test series in several different geologies have also involved 1000-lb charges [11], and the resulting data are summarized in Figure 6. As was the case for the 256-lb charges, the 1000-lb charge data suggest that the crater volumes from near-surface bursts in wet soil are approximately 4 times those in dry soil.

Data from higher yield cratering experiments are in insufficient quantity to derive near-surface height-of-burst curves for other specific yields and geologies. However, the cratering efficiency ($\overline{V}/Y$) of one geology can be compared to that of another geology. As indicated in the previous section, such cratering efficiency appears to be yield-independent for near-surface explosions to within the scatter of available data.

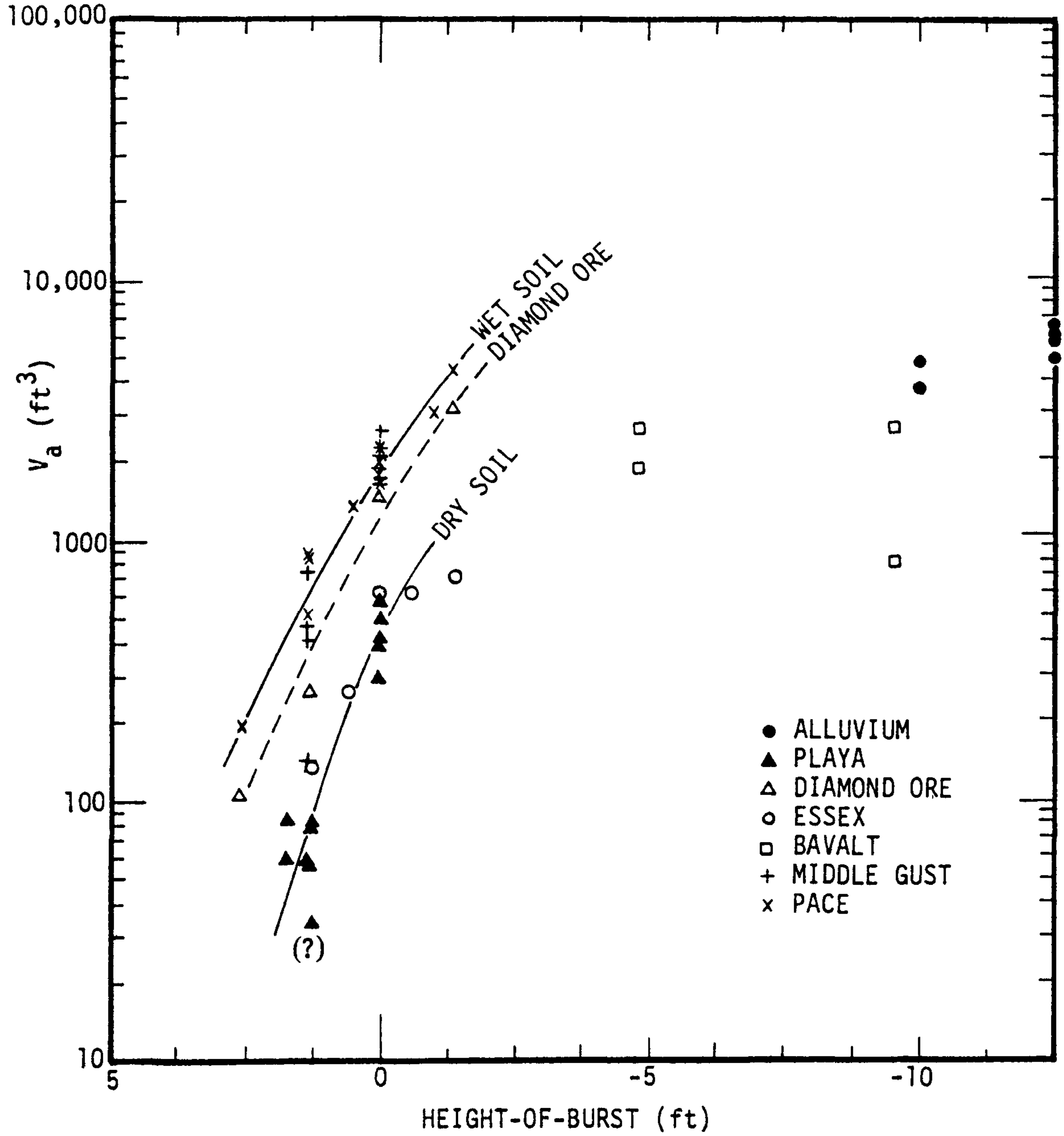

Figure 6. Crater Volume from 1000-lb HE Explosions in Soil

When cratering efficiency is plotted vs scaled height-of-burst for a large number of experiments and various geologies, the scaled height-of-burst curves for the different geologies appear to have the characteristic shapes summarized by the best estimate curves in Figure 7. Thus, to a good approximation, the cratering efficiency data are correlated by Equation 2, i.e.,

$$V(G, HE, H) = V_o(G, HE)F(HE, H) \qquad (5)$$

After study of the data, cratering efficiencies for zero height-of-burst were estimated for each medium illustrated in Figure 7. These estimates for $V_o(G, HE)$ and Equation 2 allow us to plot the cratering efficiency data in normalized form, from which we can obtain a relationship for the shape factor F(HE, H). As shown in Figure 8, a reasonable estimate of the shape factor is

$$F(HE, H) = e^{-5.2H} \text{ for } |H| \lesssim 0.4 \qquad (6)$$

which approximates the logarithmic mean of data scatter.

The cratering data can be combined into subgroups of dry soil, wet geologies (including soils and clay shales), dry soft rocks, and dry hard rocks as illustrated by Figures 9 through 12. Table 1 summarizes the cratering efficiencies and K(G) for this more generic classification (as opposed to distinguishing between dry alluvium and dry playa, dry clay, dry sand, etc.). These results will be useful later in predicting crater volumes from nuclear sources.

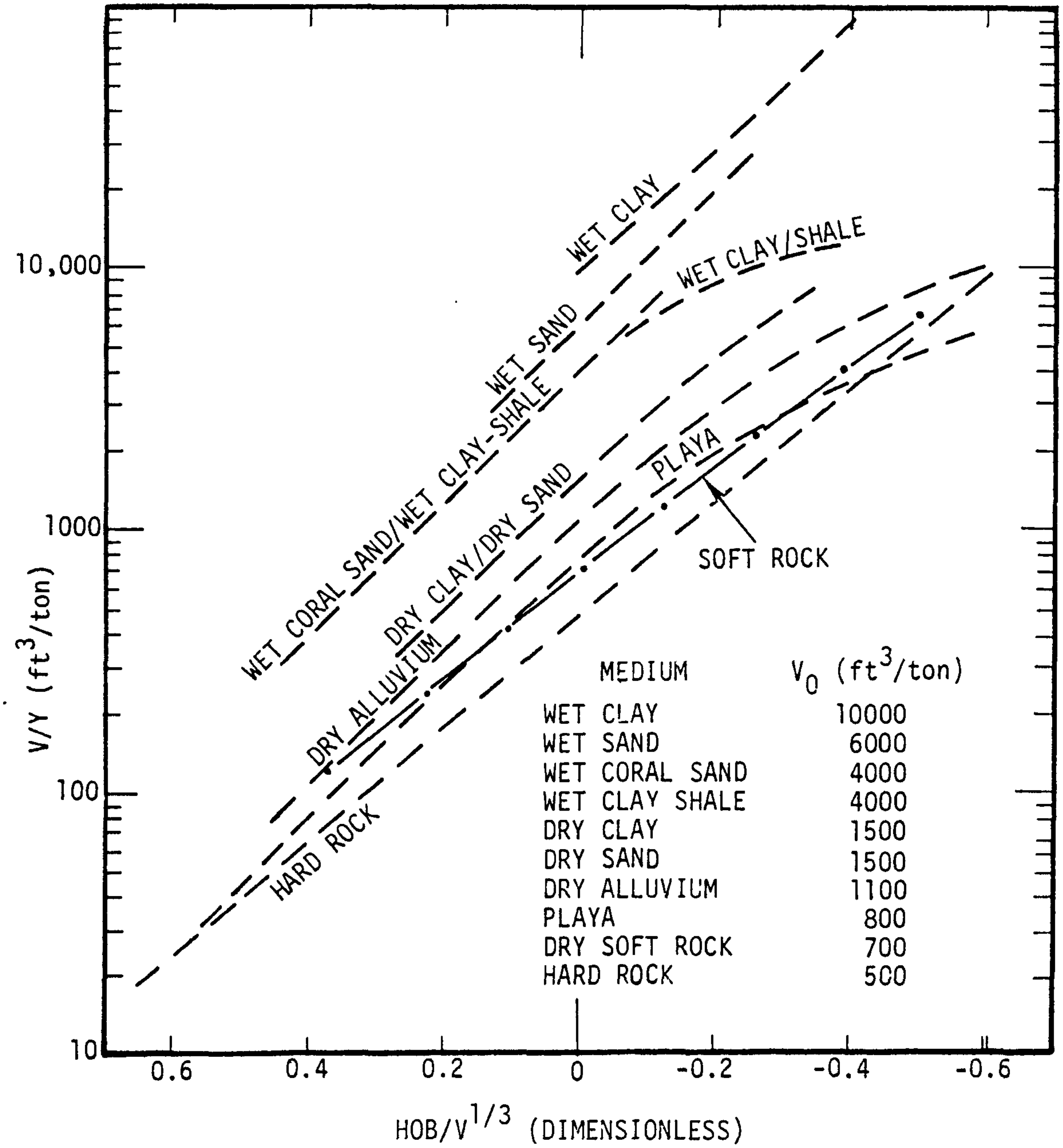

Figure 7. Summary - Best Estimate Near-Surface HE Cratering Efficiency

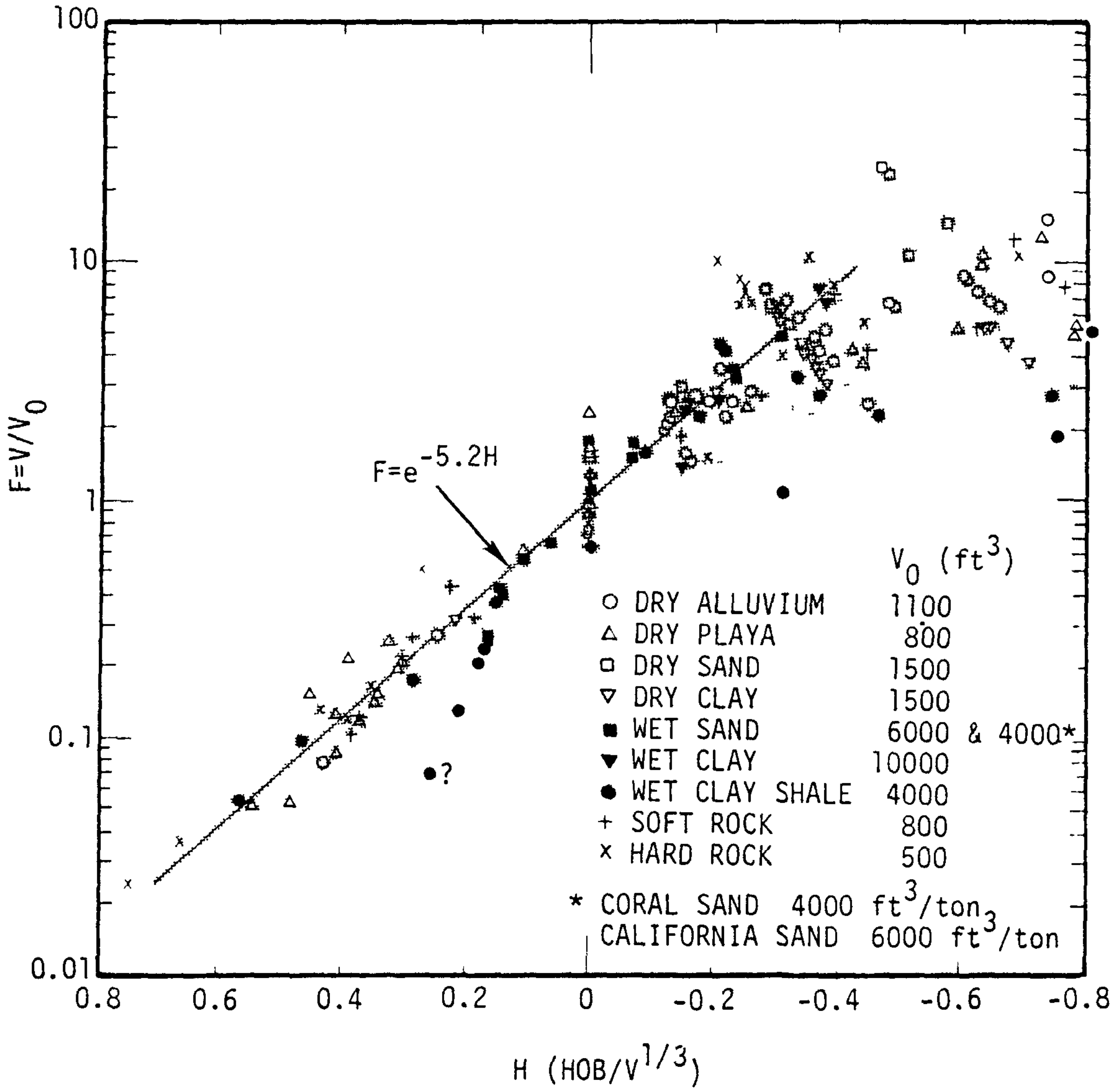

Figure 8. Normalized Cratering Efficiency for Various Geologies

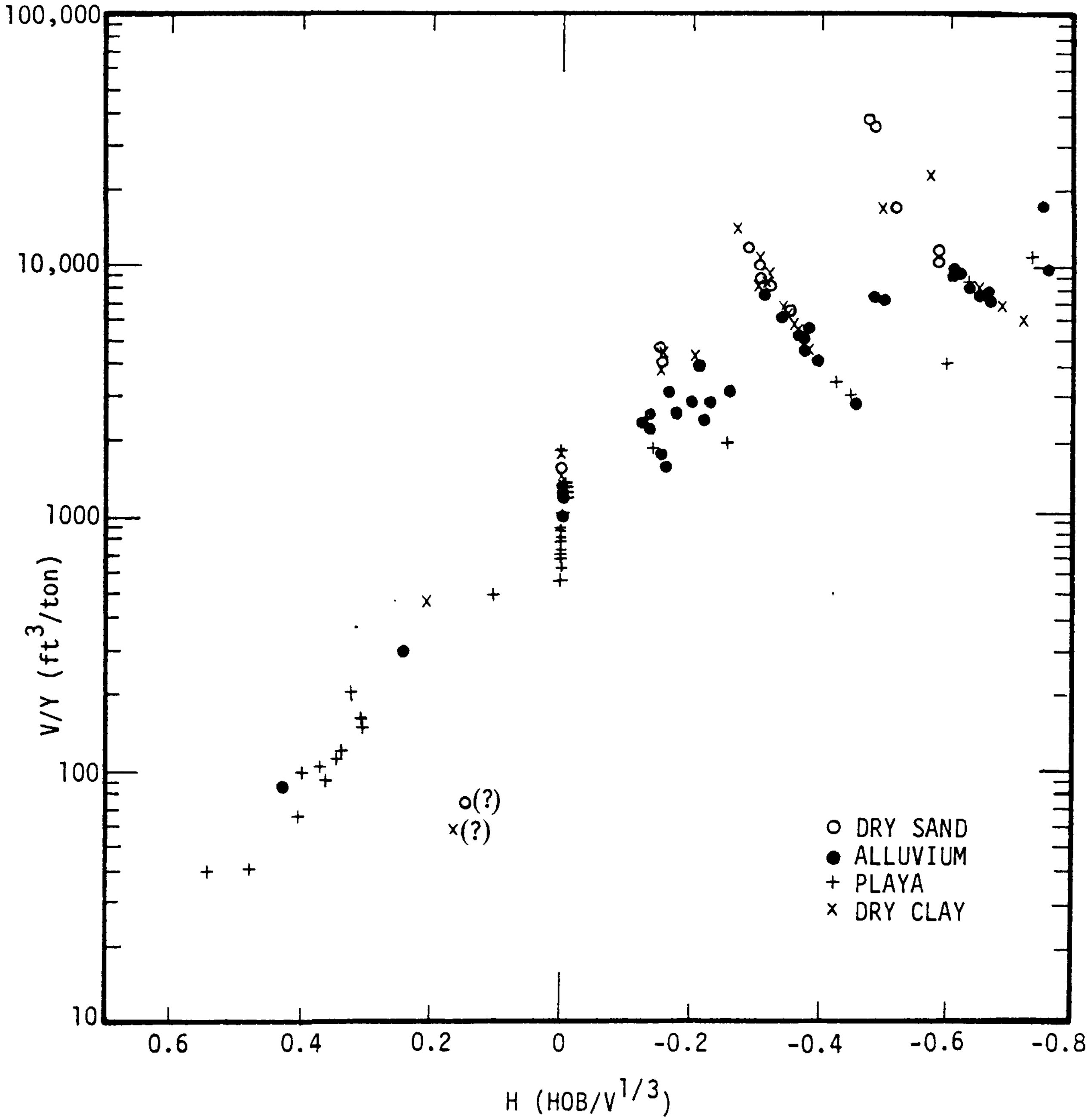

Figure 9. Near-Surface HE Cratering Efficiency in Dry Soil

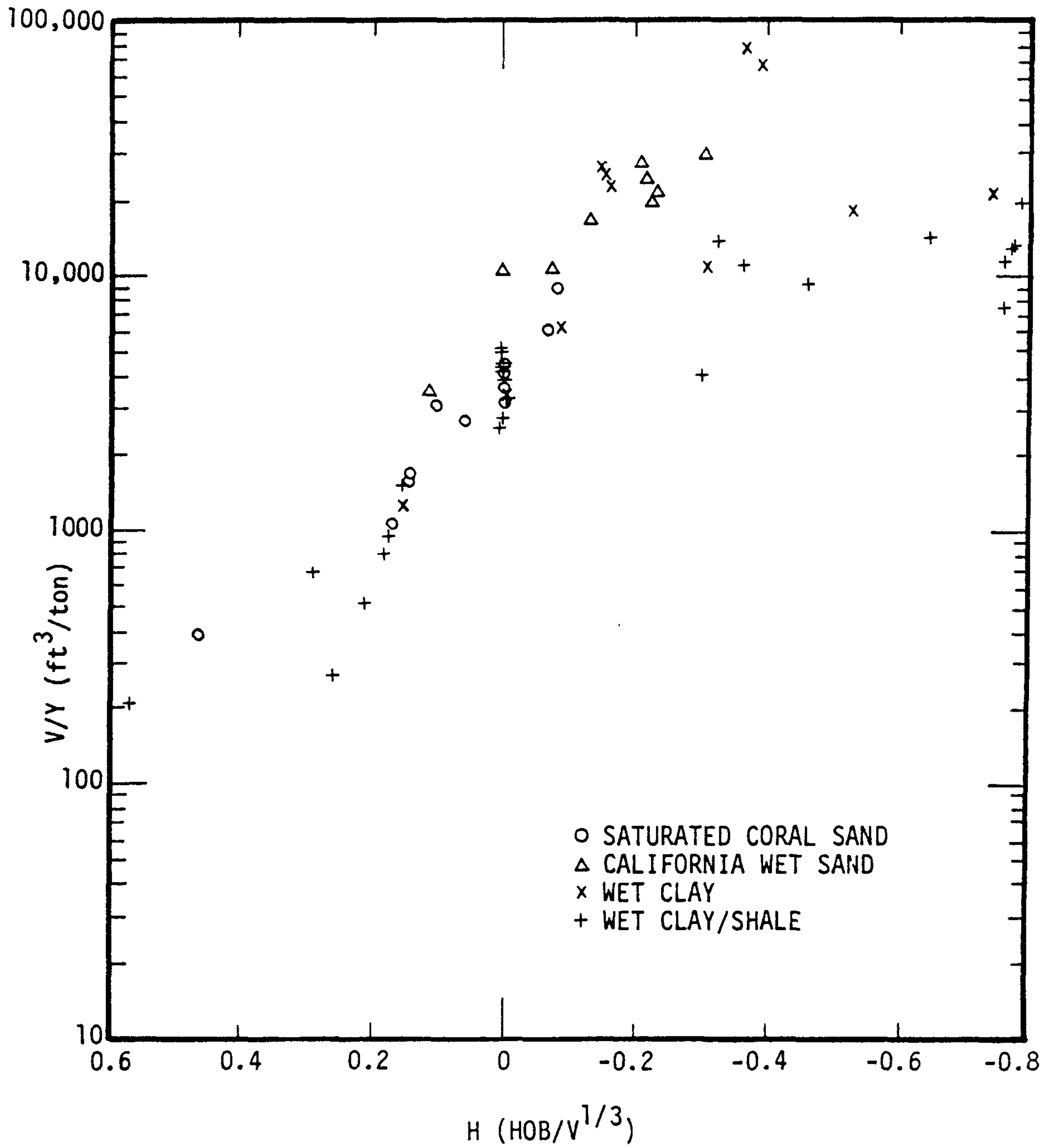

Figure 10. Near-Surface HE Cratering Efficiency in Wet Geologies

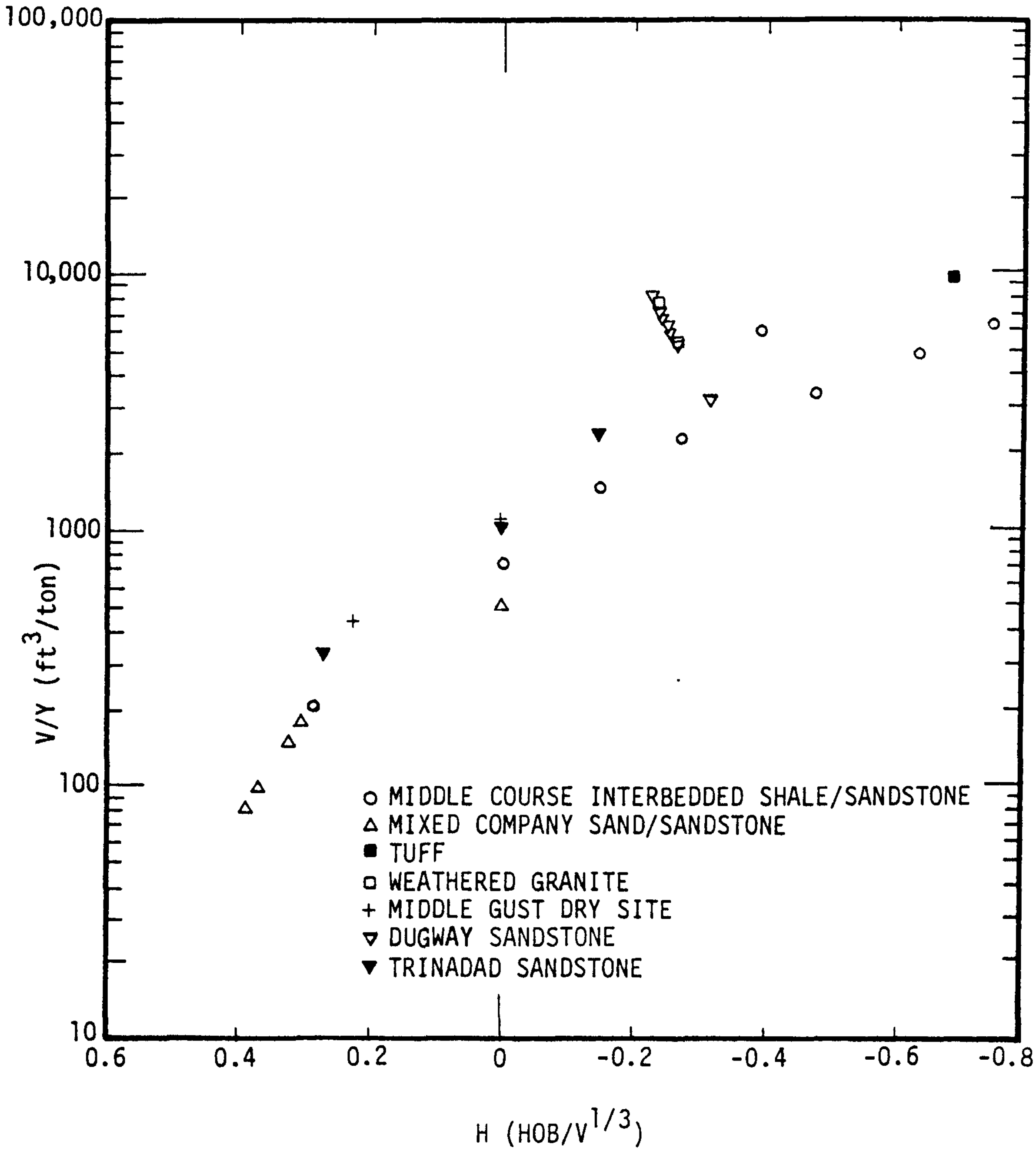

Figure 11. Near-Surface HE Cratering Efficiency in Soft Rock

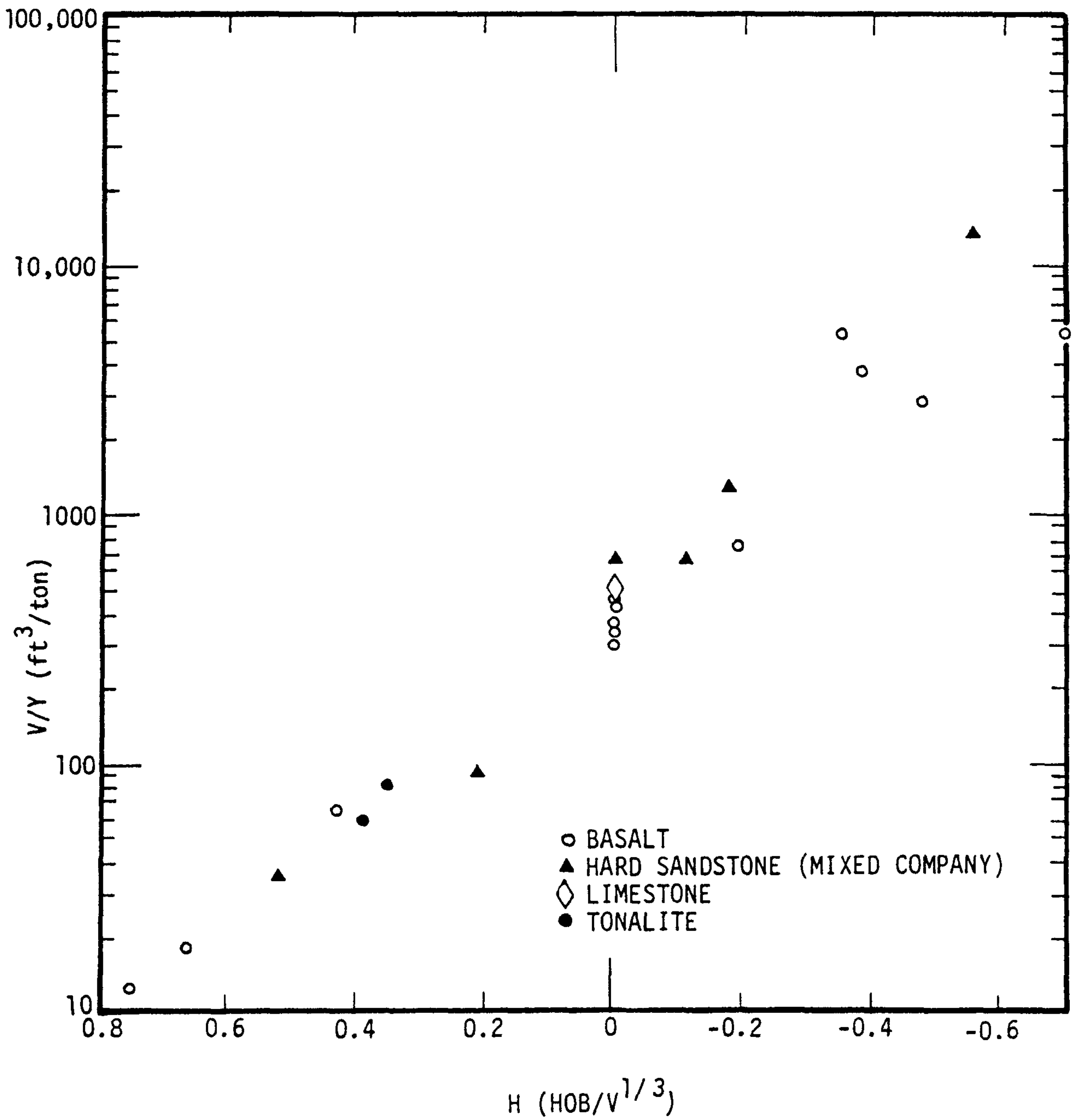

Figure 12. Near-Surface HE Cratering Efficiency in Hard Rock

Table 1. HE Cratering Efficiency for Generic Geologic Materials

MEDIUM (G)	V_o(G,HE) - FT^3/TON		k(G)*	
	RANGE	BEST ESTIMATE	RANGE	BEST ESTIMATE
WET SOIL	2000-8000	4000	0.5 - 2	1
DRY SOIL	600-1800	1000	0.15 - 0.45	0.25
SOFT ROCK	500-1200	800	0.125 - 0.3	0.2
HARD ROCK	300- 700	500	0.075 - 0.175	0.125

*BASED ON $V_o(G_o$,HE)=4000 FT^3/TON FOR WET PACIFIC CORAL SAND

3.2 NUCLEAR CRATERING EXPERIENCE

The available cratering data from near-surface nuclear bursts are from six low-yield events in the dry soil (alluvium and playa) at NTS, one low-yield cavity experiment in granite, one low-yield event (performed by the British) in limestone over sand, and ten moderate- to high-yield events in Pacific saturated coral. Table 2 summarizes the unclassified data used here. Two of the Pacific sources, KOA and SEMINOLE, were detonated in large water tanks that significantly reduced the energy density of the effective explosive source. The energy density of the KOA source (including the water tank) was consistent with that for the kiloton-level sources used at NTS, and the SEMINOLE source had an energy density within an order of magnitude of that for HE. Most of the remaining Pacific sources were surrounded by experimental apparatus (and sheds of various sizes and shapes). If one ignores the mass of the barges below the source, at least some tests involved sources with energy densities that approach the yield-to-mass ratios of modern RVs. However, the radiative characteristics of these sources have not been evaluated and compared to modern weapon characteristics.*

---

*It is not yet clear whether or not any of the high energy density nuclear sources coupled a significant amount of energy to the ground by radiation. It is clear that many of the Pacific sources, herein referred to as high energy density sources, did not couple a significant amount of energy via radiation. However, some Pacific devices which may have been radiative sources appear to have had cratering efficiencies comparable to non-radiative sources.

Table 2. Crater Parameters for Nuclear Cratering Events

EVENT	YIELD	HOB (ft)	MEDIUM	R_a (ft)	D_a (ft)	V (ft^3)	V/Y (ft^3/ton)	$HOB/V^{1/3}$	$R/V^{1/3}$	$D/V^{1/3}$
JANGLE S	1.2 kT	+3.5	ALLUVIUM	45	17	4.45×10^4	37	+0.099	1.27	0.48
JANGLE U	1.2 kT	-17	"	129	53	1.32×10^6	1100	-0.155	1.18	0.483
TEAPOT ESS	1.2 kT	-67	"	146	90	2.6×10^6	2166	-0.49	1.06	0.654
JOHNIE BOY	0.5 kT	-1.75	"	61	30	1.4×10^5	280	-0.034	1.17	0.578
SEDAN	100 kT	-635	"	608	323	1.8×10^8	1800	-1.12	1.08	0.572
IVY MIKE	10.4 MT	10	PPG	3275	187	1.44×10^9	138	0.0089	2.9	0.166
CASTLE BRAVO	15 MT	7	"	3180	225	2.01×10^9	134	0.0055	2.52	0.178
CASTLE KOON	150 kT	9.3	"	538	75	1.5×10^7	100	0.038	2.18	0.304
CACTUS	18 kT	3	"	173	37.2	1.99×10^6	111	0.024	1.38	0.296
OAK	9 MT	6.5	"	3200	203	1.83×10^9	203	0.0053	2.62	0.166
KOA	1.3 MT	3	"	2310	171	8.11×10^8	624	0.0032	2.48	0.183
ZUNI	3.4 MT	9.6	"	1145	113	2.04×10^8	60	0.016	1.94	0.192
TEWA	4.6 MT	12.3	"	2160	129	7.63×10^8	164	0.013	2.36	0.141
LACROSSE	39.5 kT	8	"	200	46.5	3.06×10^6	77	0.055	1.38	0.32
SEMINOLE	13.7 kT	7	"	324	32.2	6.99×10^6	510	0.037	1.69	0.168
DANNY BOY	0.42 kT	-110	BASALT	107	62.3	1.13×10^6	2680	-1.056	1.03	0.598
SCHOONER	31 kT	-355	TUFF	426	208	6.16×10^7	1987	-0.899	1.08	0.527
CABRIOLET	2.3 kT	-171	RHYOLITE	179.4	116.4	4.86×10^6	2113	-1.01	1.06	0.687
PALANQUIN	4.3 kT	-280	"	119.1	78.7	1.26×10^6	293	-2.59	1.10	0.729

In most cases, the Pacific craters breached the lagoon and were severely water washed. Furthermore, the large yield sources in the Pacific coral produce shallow dished shape craters rather than "standard" bowl-shaped crater profiles. Possible causes for such shallow craters are discussed in Section 4. Estimates of the apparent crater volume include an estimate of the amount of water ejected by the cratering action; such estimates may be subject to considerable disagreements between investigators. Because of the recent emphasis on determining crater volumes, the crater volumes for all of the Pacific craters have been re-calculated by the Air Force Weapons Laboratory, and Table 2 summarizes these more recent results [2] along with the crater parameters for various other nuclear bursts. However, we assume a factor of 2 uncertainty in these estimates of the actual crater volume to account for test-to-test variations, the effects of post-event slumping, water washing, etc. Although this assumption is arbitrary, it does not seem unreasonably large, especially in view of the reproducibility observed in HE cratering events as discussed previously.

When examining the Nevada Test Site data, one is faced with the fact that not a single source was detonated at a scaled height-of-burst directly comparable to any Pacific test. Furthermore, one of the two detonations that were closest to the surface (JANGLE S and JOHNIE BOY) involved source conditions that may have affected the cratering efficiency. The soil under JANGLE S was excavated prior to the test in order to allow for the placement of instrumentation, and then the excavation was refilled with disturbed soil. The depth of this excavation turned out to be within a couple of feet of the apparent crater depth; therefore, the crater produced by the JANGLE S source may have been affected. To account for such variables, and in view of other factors that could affect the test reproducibility, we assume a factor of 2 uncertainty associated with each of the NTS data points for crater volume.

Figure 13 shows the cratering efficiency of the Nevada Test Site near-surface data. The shaded region is an estimate of the overall uncertainty band, and the solid line through the center is a best estimate height-of-burst curve for "low energy density" nuclear sources in Nevada Test Site dry soil. The adjusted KOA and SEMINOLE data points were derived by using Equation 4 to reduce their measured volumes by a factor of 4 to account for the wet to dry soil conversion as suggested by the high-explosive data discussed in the previous section.* The best estimate NTS dry soil cratering efficiency for low energy density sources at H = 0 is 175 ft^3/ton. Based on the factor of 4 wet-to-dry soil conversion, the cratering efficiency of "low energy density" nuclear sources in saturated Pacific coral is 700 ft^3/ton (at H = 0).

Using 175 and 700 ft^3/ton as the normalizing cratering efficiency for NTS soil and Pacific coral, one can draw a normalized cratering efficiency curve vs scaled height-of-burst, such as that shown in Figure 14. For small scaled heights-of-burst, Figure 14 suggests that the height-of-burst shape factor for low energy density sources ($S = NE_\ell$) can be approximated by

$$F(NE_\ell, H) \approx e^{-15H} \text{ for } |H| \lesssim 0.06 \qquad (12)$$

Figure 15 shows the cratering efficiency data for the high-yield nuclear tests at Eniwetok and Bikini. The error bars represent the "uncertainty" as determined by the <u>assumed</u> factor of 2 uncertainty in determining the crater volume for any given test geometry. The JANGLE S and JOHNIE BOY "data points" result from multiplying their measured cratering efficiency by 4, i.e., by applying Equation 4 where K(G) was taken as 1/4,

---

*Historically, the KOA and SEMINOLE data were used to estimate the cratering efficiency of low energy density nuclear sources in Pacific coral, and based on a comparison with the cratering efficiency of low energy density nuclear sources in NTS dry soil, a factor of 4 to 6 difference was predicted as shown in Figure 5 [1]. The high-explosive tests [10] were consistent with the factor of 4 limit of the prediction.

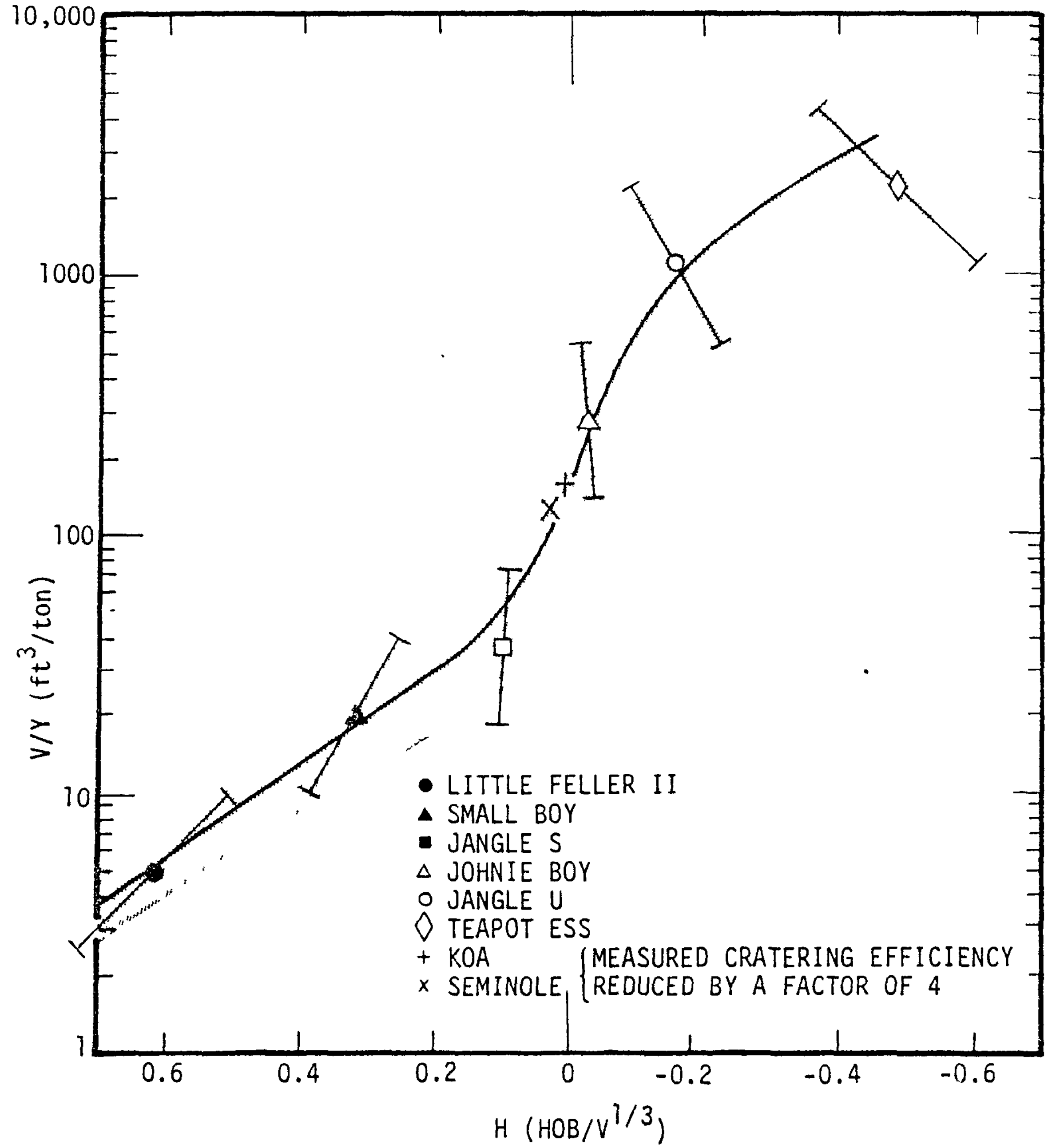

Figure 13. Cratering Efficiency of Low Energy Density Nuclear Sources in NTS Dry Soil

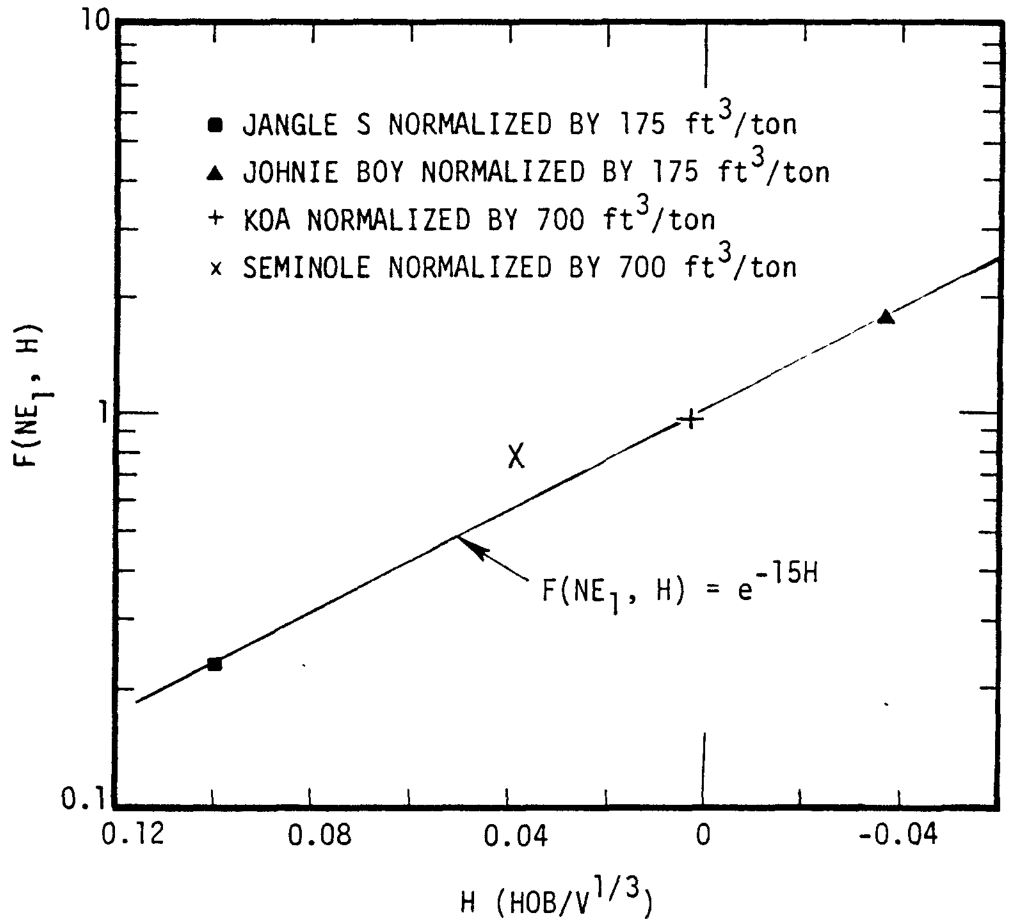

Figure 14. Normalized Cratering Efficiency Curves for Low Energy Density Nuclear Sources

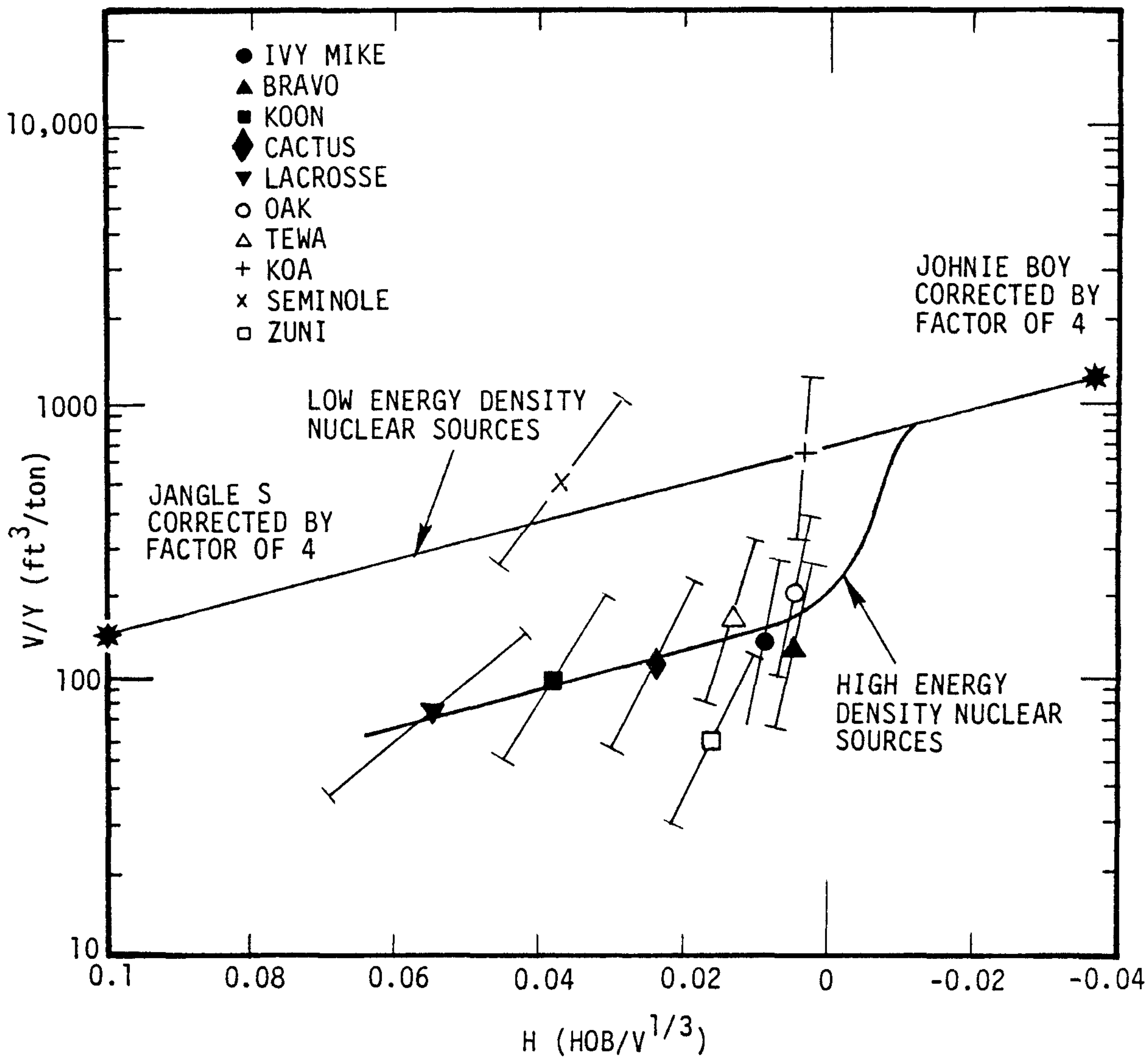

Figure 15. Cratering Efficiency of High Yield Nuclear Sources on Pacific Coral

based on the high-explosive experiments for wet and dry soil. The best estimate curve in Figure 15 can be normalized by $V_o(G_o, NE_n) \simeq 200$ ft^3/ton to derive a best estimate cratering efficiency height-of-burst curve for near-surface, high-yield high energy density nuclear explosions ($F[NE_h, H]$) as illustrated by Figure 16.

The shaded region in Figure 16 represents the author's estimate of uncertainty in predicting the cratering efficiency. The dashed lines represent the estimated variation of cratering efficiency associated with the scatter of the Pacific Test data. The larger uncertainty for above-surface explosions reflects the fact that calculations of craters from modern weapons produce significantly smaller craters than would be expected if the Pacific data are representative of modern weapons. (The Pacific nuclear test data are given more weight in making a best estimate of height-of-burst effects pending validation of the theoretical calculations.) The tamping of even shallow depths-of-burial (5-10 ft makes the nuclear source essentially a hydrodynamic source and reduces the effects of uncertainties in our theoretical understanding of close-in radiation deposition and bomb debris/ground interaction. Similarly, the uncertainty reduces with increasing height-of-burst as the importance of source details decrease.

3.3 CRATERING EFFICIENCY OF NEAR-SURFACE NUCLEAR EXPLOSIONS IN VARIOUS GEOLOGIES

Once the cratering efficiency of a given medium is known for zero height-of-burst ($V_o(G, NE_h) = K(G)V_o(G_o, NE_h)$), Equation 4 with $F(NE_h, H)$ given by Figure 16 may be used to determine the cratering efficiency for near-surface heights- (or depths-) of-burst. However, this methodology is inconvenient to use in predicting cratering efficiency because the dependent variable $\overline{V}^{1/3}$ has been used to normalize the height-of-burst data. As suggested by Reference 2, a more convenient height-of-burst curve can be derived using the locus of points

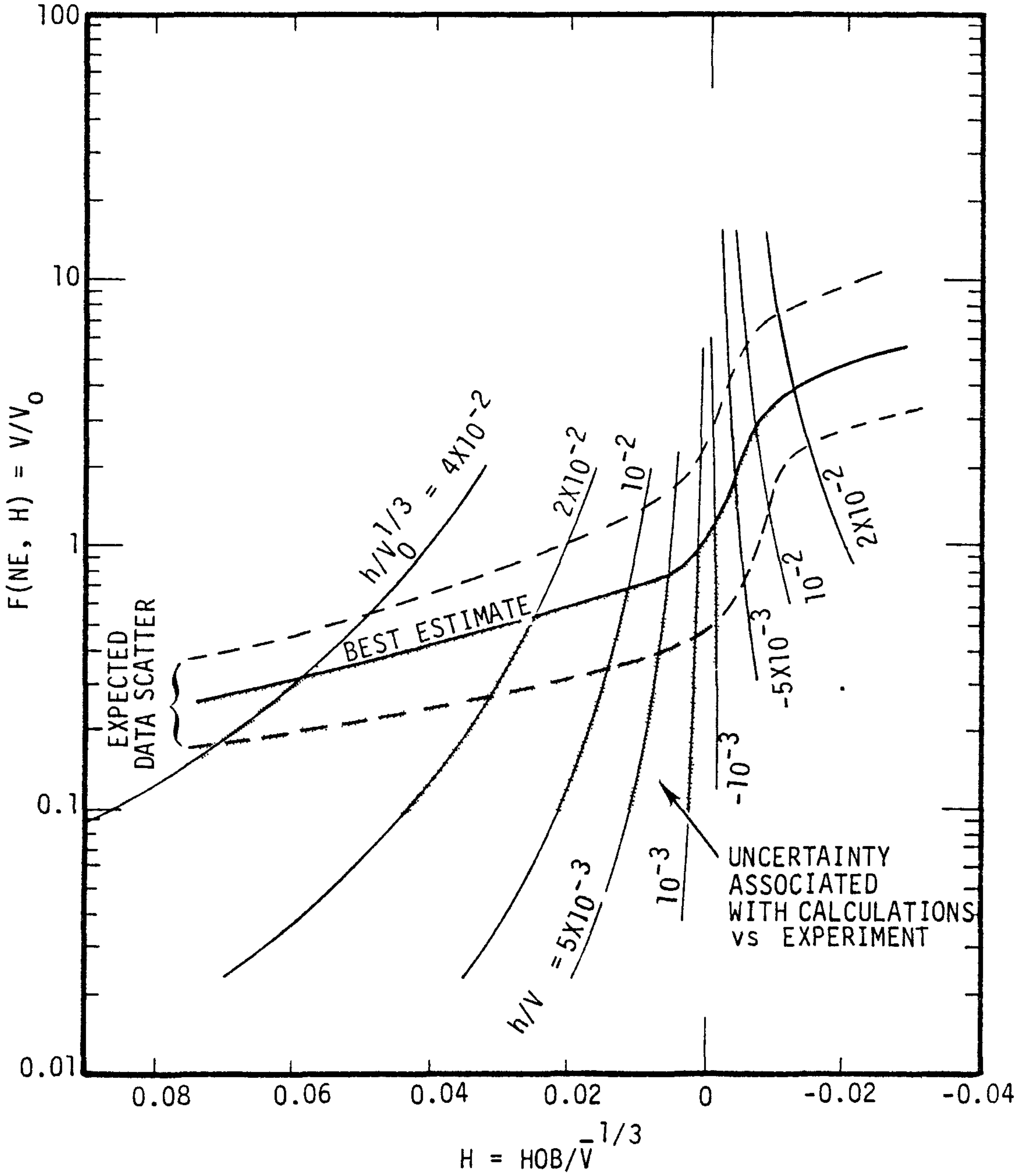

Figure 16. Normalized Cratering Efficiency Height-of-Burst Curve for High Energy Density Nuclear Sources

$$\bar{V}/\bar{V}_o = (\bar{V}/h^3)\ (h^3/\bar{V}_o) = (h/\bar{V}_o^{1/3})^3/H^3 \qquad (13)$$

to transform Figure 16 into Figure 17. Here $\bar{V}_o = YV_o$ is the crater volume for yield Y at zero height-of-burst, and Y is the weapon yield which produces the crater volume $\bar{V}$ at a height-of-burst h. Note from Equation 2 that $F(S,H) = (\bar{V}/Y)\ V_o(G,S) = \bar{V}/\bar{V}_o$. Here, $\bar{V}_o^{1/3} = K(G)\bar{V}_o(G_o,S)$ is known or can be estimated for a given medium by determining K(G) from HE cratering data and noting that $V_o(G_o,NE_h) \simeq 4000\ ft^3/ton$. Estimates so derived for several geologic media are given in the table on Figure 17.

The best-estimate curve and table in Figure 17 can be used to generate best-estimate cratering efficiency height-of-burst curves for several "uniform" geologies as given by Figure 18. The increase in cratering efficiency for depths-of-burst between 0 and 5-10 ft is produced by the trapping of radiatively coupled energy in the ground. Each of these curves is estimated to be uncertain by the amount indicated in Figure 17. Although variations in geologies can lead to substantial variations in cratering efficiency, systematic differences in cratering efficiency from two generically different geologies may in some cases be less than the estimated uncertainty in predicting the cratering efficiency in either geology.

The crater volume from bursts in layered media, e.g., dry soil over hard rock, may be reasonably estimated by the Air Force Design Manual procedure [2] which is illustrated in Figure 19. There, V_u and V_L are the apparent crater volumes for bursts on uniform media composed of the upper and lower geologies as defined by the above procedure. The shaded region represents the scatter in data from experiments in various two-layer geologic systems. Thus, if the surface layer is deeper than the crater depth, the crater volume is approximately that

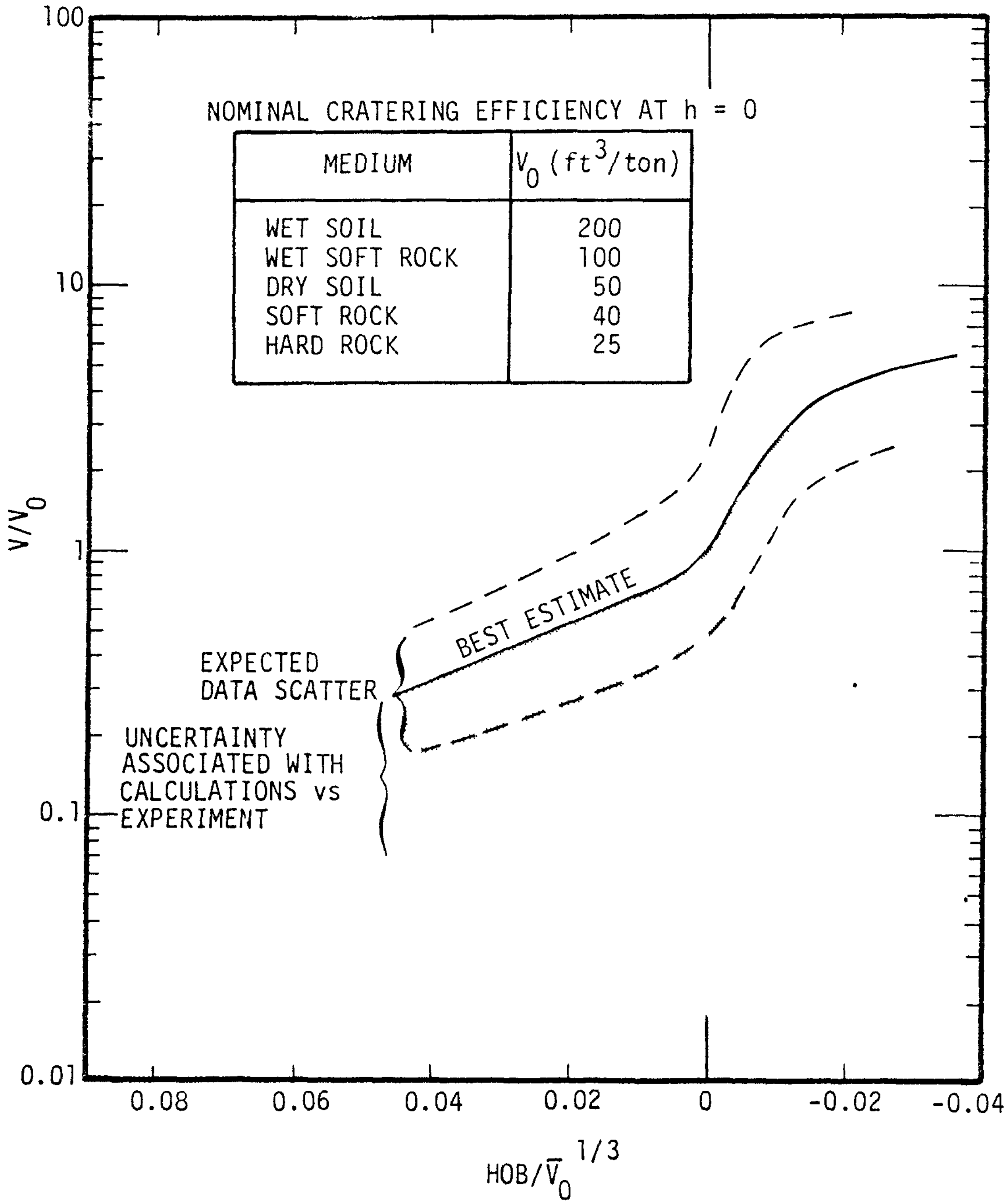

Figure 17. Normalized Cratering Efficiency for Near-Surface Bursts of High Energy Density Nuclear Sources

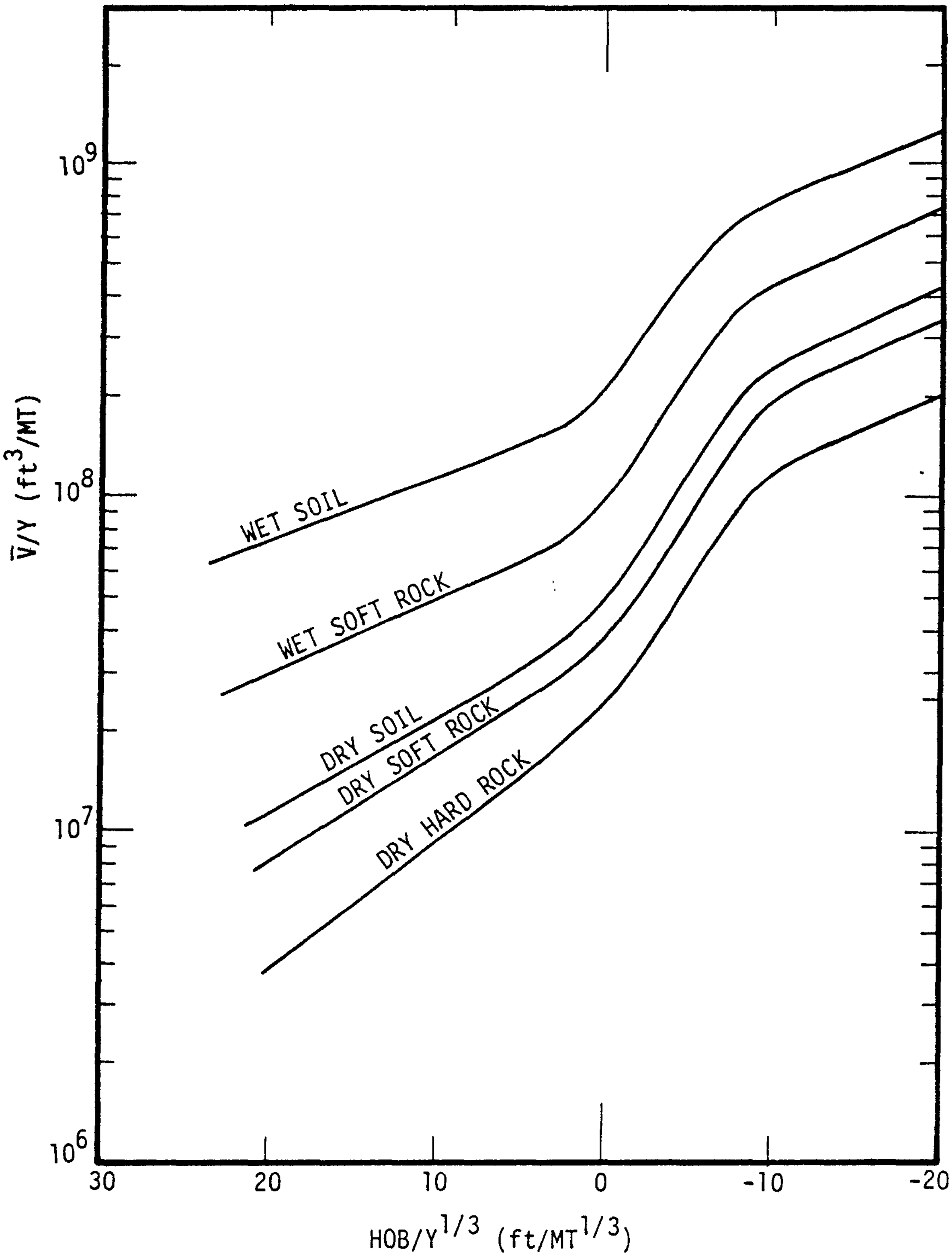

Figure 18. Best-Estimate Cratering Efficiency for Near-Surface Bursts of Modern Weapons on Various Generic Geologies

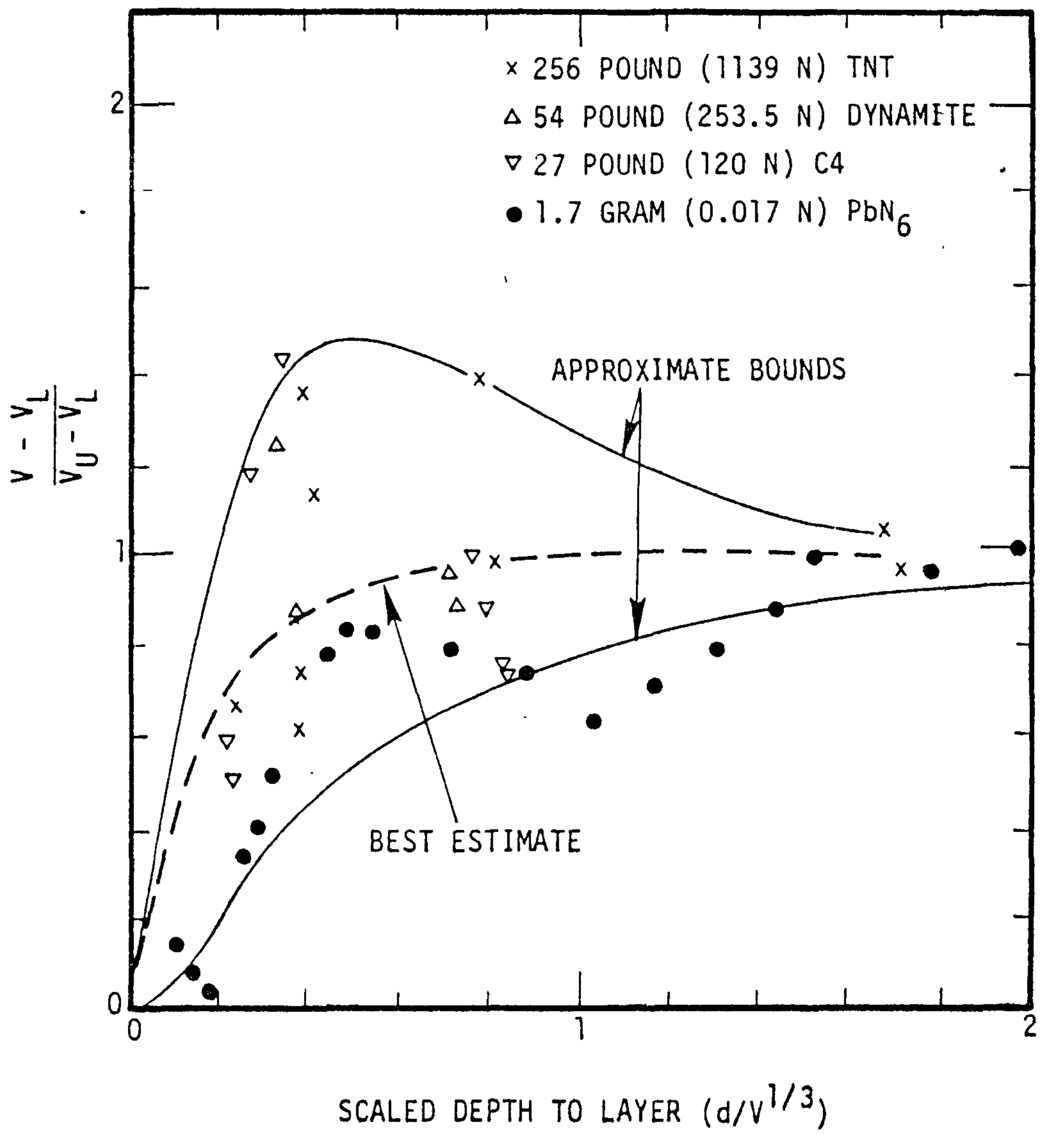

Figure 19. Estimates of the Crater Volume for Explosions in a Layered Geology

which would be computed for a burst in a uniform media composed of the surface geology. If the surface layer is thin compared to the crater depth, the crater volume is approximately that which would be estimated for a burst in a uniform media composed of the deeper geology. If the interface intersects the crater, it is expected that the crater volume will be between these two limiting cases. However, as noted in Figure 19, there are data from small high-explosive tests that suggest the crater in a layered medium could be larger than the craters from the same source in the uniform media that compose the two layers.

4. ESTIMATES OF CRATER RADIUS AND DEPTH

This section correlates data from cratering events to provide an empirical basis for estimating the crater radius and depth once the crater volume has been estimated with the procedures discussed in the previous section.

Figure 20 correlates crater radii and depth with crater volume for high-explosive and nuclear sources in dry soil, soft rock, hard rock and wet soil. More than 95 percent of all the data from explosions in dry soil, soft rock and hard rock are consistent with

$$\left.\begin{aligned} 1.1\ V^{1/3} \lesssim R \lesssim 1.4\ V^{1/3} \\ 0.35\ V^{1/3} \lesssim D \lesssim 0.7\ V^{1/3} \end{aligned}\right\} \qquad (14)$$

These constraints are consistent with the best estimates given previously [1,2], e.g., $R \simeq 1.2\ V^{1/3}$ and $D \simeq 0.5\ V^{1/3}$. The crater radii and depths provided by these best estimates are consistent with parabolically shaped craters, i.e., $V \simeq 1.5\ R^2 D$. Although the majority of the data so described are from high-explosive experiments that produced crater volumes in the range $10 \lesssim V \lesssim 10^5$ ft^3, the data from buried nuclear sources in dry soil and rock with $V \lesssim 2 \times 10^8$ ft^3 are also found to be consistent with Equation 14. Furthermore, as will be discussed shortly, Equation 14 is consistent with observed characteristics of terrestrial, lunar, and planetary meteor impact craters with apparent crater volumes up to about 10^{12} ft^3. (Based on the cratering efficiencies in the previous section, such a volume would correspond to a surface-burst explosion with a yield on the order of $\sim 10^4$ megatons.)

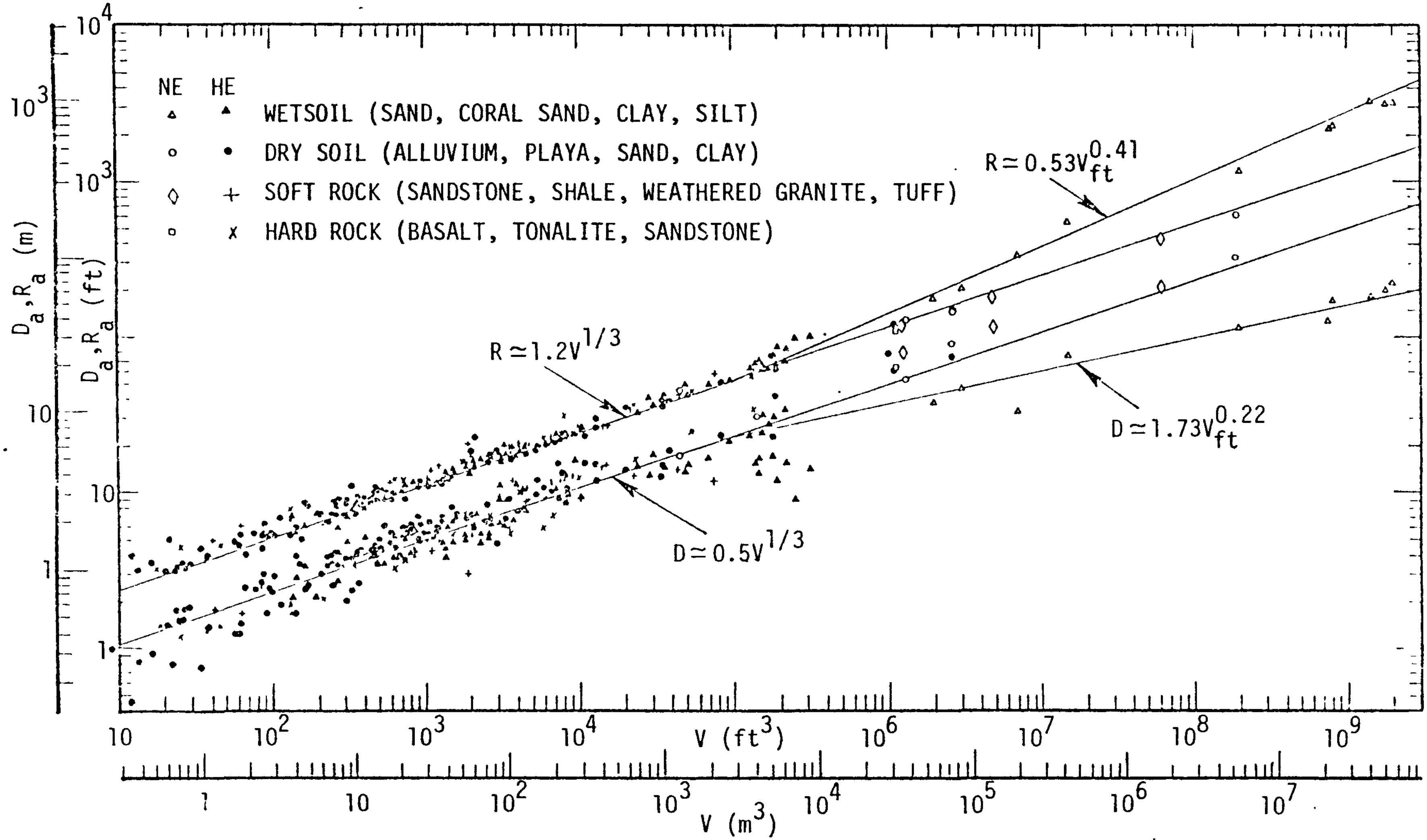

Figure 20. Crater Radii and Depths as a Function of Crater Volume

Craters from high-explosive sources in wet soil are also consistent with Equation 14 for $V \lesssim 10^5\ ft^3$, but larger craters tend to be shallower. In particular, craters from the large yield nuclear tests in saturated Pacific coral sand/coral rock become increasingly shallower with increasing crater volume, and their radii and depths are consistent with

$$\left.\begin{array}{l} 0.5\ V^{0.41} \lesssim R \lesssim 0.6\ V^{0.41} \\ 1.2\ V^{22} \lesssim D \lesssim 2.4\ V^{0.22} \end{array}\right\} \qquad (15)$$

Figure 21 compares the rim diameter and depth data from high-explosive, nuclear and meteor impact sources. The high-explosive and nuclear craters other than the large yield Pacific craters are consistent in shape with the meteor impact craters (on the earth, the moon and Mercury) with radii $\lesssim$10,000-15,000 ft [12,13]. With the exception of the large yield Pacific data and impact craters on the moon and Mercury with radii greater than 10,000-15,000 ft, the crater rim diameter-to-depth ratio is about 4, which is consistent with $R_a \simeq 2.5\ D_a$ as suggested by Equation 14, provided the rim diameter is 25 percent greater than the apparent crater diameter. The large yield Pacific cratering data and meteor impact crater data for crater radii greater than 10,000-15,000 ft deviate from this approximately invariant R/D and become increasingly shallower with increasing size. The mechanisms leading to this transition are not well understood for either the nuclear explosions or meteor impact data. With the exception of water washing effects, which affected the Pacific crater data, the explosive and impact cratering communities have suggested similar mechanisms to explain the observations (see Gault et al. [14] for a discussion of possible mechanisms for explaining the meteor impact crater shapes). Although the evidence is inconclusive, the author's view is that the most important effect that could lead to the change

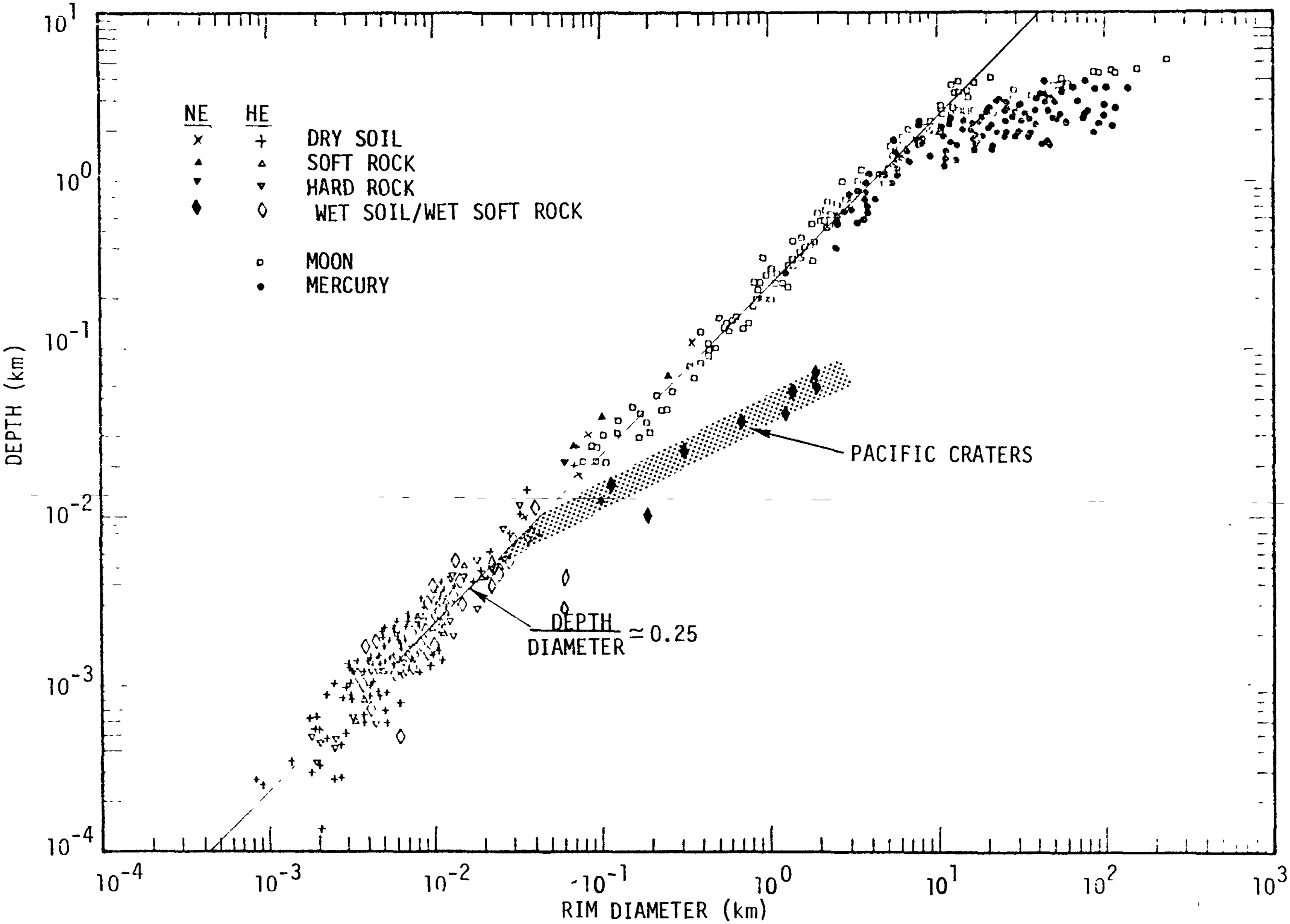

Figure 21. Explosion and Impact Crater Dimensions

in phenonema implied by the knees in Figure 21 is late stage flow phenomena that occur when stress gradients produced by gravity forces are greater than the material strength.* Laboratory tests for both high-explosive and impact craters in very weak materials [16,17] support this point-of-view.

Assuming that this hypothesis is true, then small craters in "sufficiently" weak materials or sufficiently large craters in stronger materials will be shallow. As in the "Z" model [18], a parameter $\rho g\ V^{1/3}/\tau_{max}$ might be considered as an indicator of the relative location of the transition point between stable deep bowl-shaped craters which obey Equation 14 and shallow dished-shaped craters. Based on the meteor crater impact data, the transition for dry materials would be expected to occur for much larger craters than those produced by large yield nuclear sources in the weak saturated coral. Thus, for nuclear sources of strategic interest it seems most likely that craters in dry soil and rock are deep bowl-shaped craters, and quantitative estimates of crater radii and depths can be obtained from Equation 14 once the crater volume is known. For sufficiently wet soils and crater depths greater than about 20 ft, shallower dished-shaped craters are expected and, based on Pacific data, radii and depths might be estimated from Equation 15.

Figures 22 and 23 summarize crater radii in various media for megaton near-surface bursts for both bowl-shaped and dished-shaped crater shapes inferred from the Pacific data in Figure 20. Here, the uncertainty bands represent the cumulative uncertainty derived from Figures 17 and 20.

---

*Another effect that could lead to flat floored craters at sizes less than those required for the lithostatic stresses to overcome the in-situ strength includes layering and late-time rebound phenomena associated with post-shock media response [15].

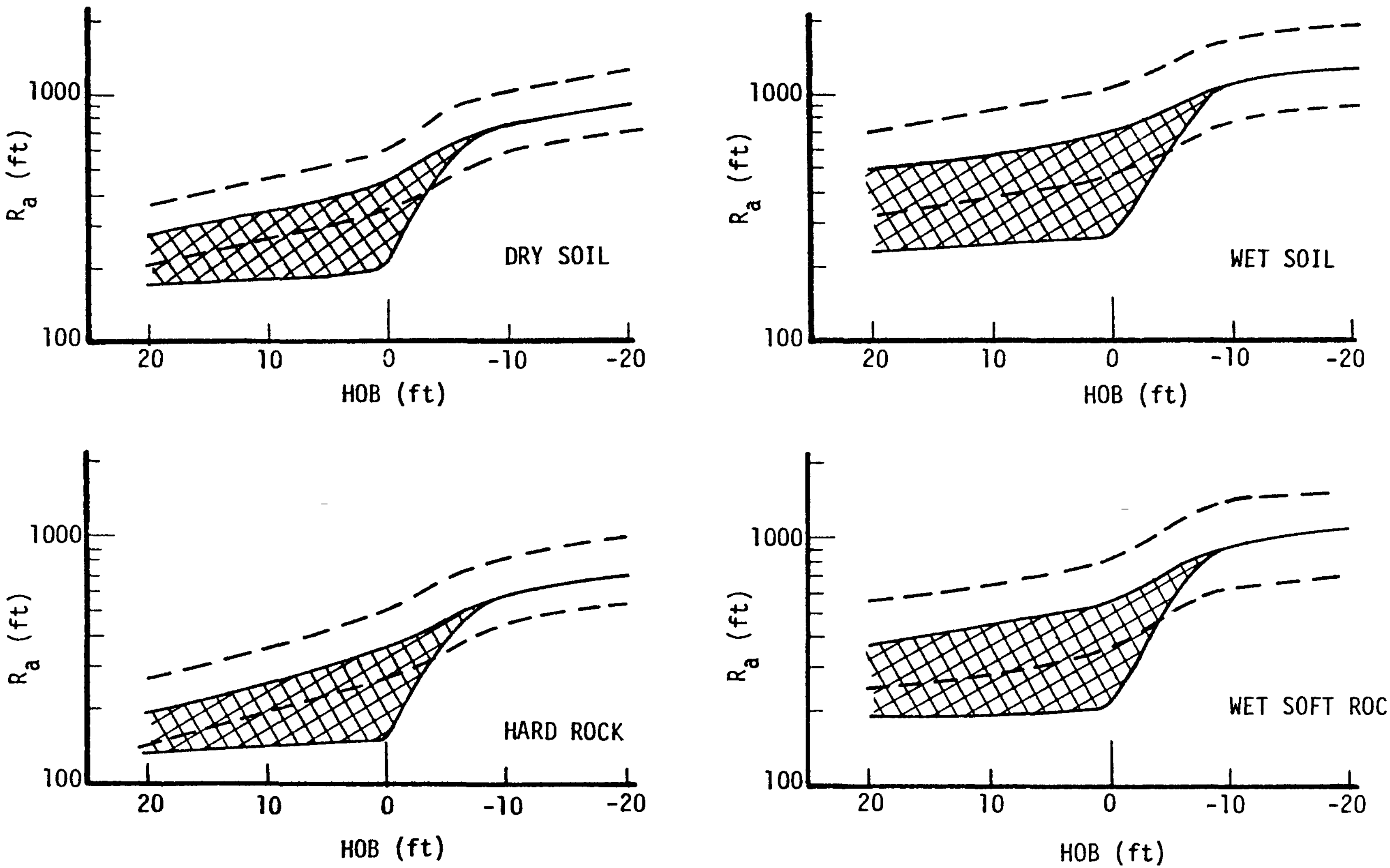

Figure 22. Crater Radii from 1-MT Near-Surface Bursts (Assuming Bowl-Shaped Craters)

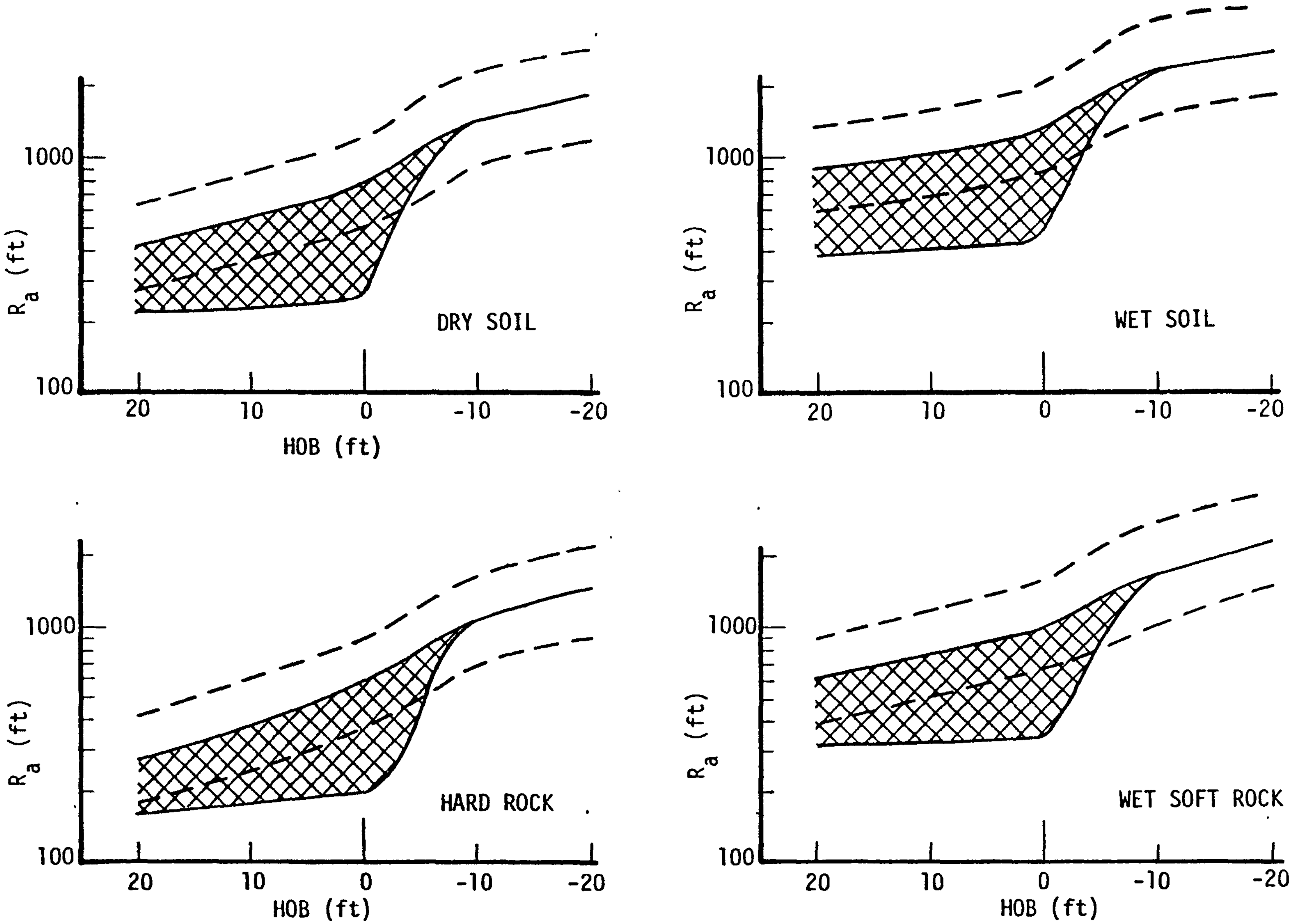

Figure 23. Crater Radii from 2-MT Near-Surface Bursts (Assuming Dished-Shaped Craters)

5. SUMMARY

The previous sections presented an empricially based methodology for estimating cratering efficiency and crater dimensions from high yield nuclear near-surface bursts in various geologies. The first step in the procedure is to estimate the crater volume. Various formulae and figures were constructed to accomplish this first step--the most convenient method is to use Figures 17, 18 and 19 to estimate the cratering efficiency for the geology and height-of-burst of interest. The second step in the prediction procedure is to estimate the crater shape by using Figure 19 or by applying Equations 14 or 15 depending on the geology.

A number of uncertainties are involved in estimates of cratering efficiency and crater dimensions so derived. Some uncertainties are associated with our knowledge of the geology; others result from our lack of understanding of the physics of energy coupling and cratering phenomena.

Based on data from high-explosive experiments, repeated explosions of a given source in a given generic geology (wet soil, dry soil, hard rock, soft rock) would be expected to produce crater volumes that vary by as much as a factor of 3 or 4 and crater dimensions that vary by a factor of as much as 50 percent. In addition to uncertainties associated with these variations, which might be taken as random variations (in view of the usual ignorance of the target geology), there exist two other sources of systematic uncertainty in estimating craters produced by large yield explosions of modern nuclear weapons: uncertainties in our understanding of the physics of energy coupling and uncertainties in predicting crater shape.

There is an order-of-magnitude discrepancy between calculations of the cratering efficiency of a modern nuclear weapon and prediction procedures based on the Pacific nuclear cratering data. If such calculations are credibly validated, then the best-estimate crater volumes recommended here would be systematically reduced by as much as an order-of-magnitude (crater dimensions would be reduced by as much as a factor of about 2).

Although a number of mechanisms have been suggested to explain the shallow dished-shaped Pacific craters, no conclusive explanation exists. In the author's opinion, the shallow Pacific crater shapes most likely resulted from late-stage cratering phenomena in which gravity forces were instrumental. If this hypothesis is correct, then large craters might be expected to be bowl-shaped in "sufficiently" strong media and dished-shaped in "sufficiently" weak media. Nuclear craters (from yields of interest) in dry soil and rock are believed to be bowl-shaped with radii that are approximately 2.5 times their depth. Based on the Pacific data, craters from large yield nuclear explosions in saturated sands and clay are believed to be dished-shaped with radii up to $\sim$15-20 times their depths. Shallow dished-shaped craters may or may not occur in wet soft (weak) rock depending on the rock strength and the explosive yield. The resulting uncertainty in predicting crater shape could lead to a factor of 2 or more uncertainty in estimates of crater radius and depth from large yield sources in soft wet rock.

The range of uncertainty in predicting the crater dimensions from explosions in a given medium can be substantially larger than the systematic variations in the crater dimensions with variations in geology. The systematic uncertainties associated with our lack of understanding of energy coupling and cratering phenomena may be reduced by further research. The "random" uncertainties (that reflect observed data scatter) probably cannot be substantially reduced.

REFERENCES

1. H. F. Cooper, On Crater-Induced Ground Motions from Near-Surface Bursts (U), Air Force Weapons Laboratory, AFWL-TR-71-72, November 1971 (Secret/RD).

2. R. E. Crawford, C. J. Higgins, and E. H. Bultman, The Air Force Manual for Design and Analysis of Hardened Structures, Air Force Weapons Laboratory, AFWL-TR-72-102, October 1974.

3. L. J. Vortman, "Ten Years of High Explosive Cratering Research at Sandia Laboratory," Nuclear Applications and Technology, Vol. 7, September 1969, pp. 269-304.

4. A. J. Piekutowski, The Effect of Variations in Test Media Density on Crater Dimensions and Ejecta Distribution, Air Force Weapons Laboratory, AFWL-TR-74-326, April 1975.

5. L. J. Vortman, personal communication, August 1976.

6. R. W. Terhune, T. F. Stubbs, and J. T. Cherry, "Nuclear Cratering on a Digital Computer," Proceedings from the Symposium on Engineering with Nuclear Explosives, January 14-16, 1970, Las Vegas, Nevada, 1970, p. 334.

7. L. J. Vortman, "Craters from Surface Explosions and Scaling Laws," Journal of Geophysical Research, Vol. 73, No. 14, 1968, pp. 4621-4636.

8. C. E. Violet, "A Generalized Empirical Analysis of Cratering," Journal of Geophysical Research, Vol. 66, No. 10, October 1961, pp. 3461-3470.

9. A. Laupa, On Scaling of Pacific Craters (U), The Rand Corporation, RM 4308-PR, October 1964 (Secret/RD).

10. H. F. Cooper, A Review of Preliminary Results from the Pacific Cratering Experiments, R & D Associates, RDA-TR-129-AF, January 1973.

11. D. M. Lockard, Crater Parameters and Material Properties, Air Force Weapons Laboratory, AFWL-TR-74-200, October 1974.

12. R. J. Pike, "Depth/Diameter Relations of Fresh Lunar Craters: Revision from Spacecraft Data," Geophys. Res. Lett., Vol. 1, No. 7, 1974, pp. 291-294.

REFERENCES (CONTINUED)

13. D. E. Gault, J. E. Guest, J. B. Murray, D. Dzurisin, and M. C. Malin, "Some Comparisons of Impact Craters on Mercury and the Moon," Journal of Geophysical Research, Vol. 80, No. 17, June 10, 1975, pp. 2444-2460.

14. W. L. Quaide, D. E. Gault, and R. A. Schmidt, "Gravitative Effects on Lunar Impact Structures," Annals of the New York Academy of Sciences, Vol. 123, Article 2, July 15, 1964, pp. 563-572.

15. G. W. Ulrich, The Mechanics of Central Peak Formation in Shock Wave Cratering Events, Air Force Weapons Laboratory, AFWL-TR-75-88, May 1976.

16. D. E. Gault, personal communication, July 1976.

17. A. J. Piekutowski, A Review of Cratering and Ejecta Studies Performed at the University of Dayton Research Institute, presented at the AFWL Cratering and Related Effects Review, Kirtland Air Force Base, New Mexico, 27 April 1976.

18. D. Maxwell and K. Siefert, Modeling of Cratering, Close-In Displacements and Ejecta, Physics International Company, DNA 3628F, 16 July 1975.