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CRATER SCALING AS A FUNCTION OF
CHARGE BURST DEPTH

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Boeing Company

Sandia Laboratories Basic Ordering
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ABSTRACT

Apparent crater dimensional scaling parameters as functions of scaled charge burst depth for explosive events in playa, desert alluvium and basalt are determined empirically. An iterative technique is used to determine a dimensional scaling exponent which is the same as the exponent used to scale charge burst depth. This results in fit tolerances and correlation coefficients which appear to be equivalent or better than those exhibited when the charge burst scaling exponent is determined arbitrarily.

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1.0 INTRODUCTION

Investigators have concluded that for desert alluvium soil, apparent crater radius is proportional to charge weight to the 0.295 power at the optimum burst depth (References 1 and 2). These studies also indicated that apparent crater depth scaled by some exponent less than 0.333 at optimum burst depth. Other investigators have found that apparent crater radius and depth scale by an exponent greater than 0.33 for surface cratering events in soil (References 3 and 4). A detailed study of references cited here leads to the conclusion that scaling exponents for crater dimensions in soil vary significantly as charge burst depth is increased from the surface to a depth which results in an optimum crater.

Apparent crater data are now available to define complete depth-of-burst curves for several charge weights in playa, and to a lesser extent, burst depth curves for desert alluvium and basalt. It is the purpose of this study to use these data to empirically determine the relationship between crater dimensional scaling parameters and charge burst depth.

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2.0 EXPERIMENTAL DATA

2.1 Playa

Apparent crater data for apparent craters in playa are given in Tables A.1 through A.4 of Appendix A. Playa consists of lightly cemented thin beds of fine silt and clay, and is uniform in lithology, both laterally and vertically. This type of soil material is commonly found in dry lake beds in the southwestern part of the United States.

In the Toboggan experiment, apparent craters were formed from 8-pound charges detonated on the Yucca dry lake bed of the Nevada Test Site (Reference 5). Apparent crater data for 64-pound charge events resulted from an experiment conducted on the Antelope dry lake bed at the Tonopah Test Range (Reference 6). Crater data for 256-pound events resulted from the Air Vent experiment on Frenchman Lake at the Nevada Test Site (Reference 3). Cratering data for 20-ton events resulted from the Air Vent and Flat Top experiments also conducted on the Frenchman dry lake bed on the Nevada Test Site (Reference 7).

Apparent crater depth-of-burst plots for playa are given in Appendix A, Figures A.1 through A.8. Smooth curves were drawn arbitrarily through data points and do not represent a mathematical fit.

2.2 Desert Alluvium

Apparent crater data for desert alluvium are shown in Appendix A Tables A.5 through A.9. The desert alluvium found in Area 10 of the AEC Nevada Test Site consists of cobbles up to 2 feet in maximum

diameter distributed throughout a matrix of gravel and sand. This material is not highly consolidated, has an in situ density of approximately 95 pounds per cubic foot and a water content of about 8 percent.

Crater data for the 256-pound events resulted from experiments conducted by Stanford Research Institute and Sandia Corporation (References 8 and 9). Craters from 1,000-pound charges resulted from the Pre-Buggy Experiment (Reference 10). The 2,560-pound crater data resulted from experiments by Stanford Research Institute and tests conducted in connection with Operation Jangle (References 11 and 12). Craters from 20-ton charges were part of the Stanford Research Institute experiments cited above and Project Stagecoach (Reference 13). The Jangle and Teapot nuclear test programs yielded 1.2 kiloton crater data (References 14 and 15).

Apparent crater depth-of-burst curves for desert alluvium are given in Appendix A, Figures A.9 through A.18. Again, smooth curves were drawn through these data arbitrarily and do not represent a mathematical fit.

2.3 Basalt

Apparent crater data for basalt are presented in Tables A.10 through A.15. Craters resulting from 25-, 75-, and 200-pound charges were in basalt found in the Panama Canal Zone (Reference 16). This basalt is a dark gray compact very hard fine grained rock closely to moderately jointed and often showing columnar structure.

Craters resulting from the 1,000-pound charges were found on Buckboard Mesa in Area 15 of the Nevada Test Site (Reference 17). This basalt of

igneous origin, is highly vesiculated at the surface and has a density of approximately 160 pounds per cubic foot. Craters formed by 4,000-pound charges were part of the MTCE Experiment at the Yakima Test Range in Washington (Reference 18). The basalt at this site is similar to that found on Buckboard Mesa, however, its density is slightly greater. Craters formed by 20-ton charges were part of the Buckboard experiment described above and the Pre-Schooner experiment (Reference 19).

The high-explosive charge for all events cited above, except for the Panama series, was either a cast TNT sphere or cast TNT blocks stacked to simulate a sphere. For the Panama series, however, charges were cylinders of pelletized TNT. This difference could influence apparent crater data and thus introduce another unknown when burst depth data are correlated.

Depth-of-burst curves for apparent craters in basalt are given in Appendix A, Figures A.19 through A.30. Smooth curves were arbitrarily drawn through data points and do not represent a mathematical fit. As can be noted, these data are quite inconsistent when compared to the soil depth-of-burst data. The only reason for including these data here is to permit this investigation to be carried to rock media. The reader is referred to the specific references cited for complete details on charge placement, medium, and other pertinent information for each cratering experiment.

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3.0 ANALYSIS AND INTERPRETATION

Using arbitrarily fitted or smoothed depth-of-burst curves for apparent crater dimensions which are given in Appendix A, the apparent crater scaling exponent b and proportionality constant K were calculated for each 0.1 of a scaled foot (crater dimension is equal KW^b). This was done using the Method of Least Squares applied to all crater dimensions existing for a given scaled burst depth. For example, on playa, complete depth-of-burst curves are available for three charge weights (8-, 64- and 256-pounds) and a partial depth-of-burst curve is available for a 20,000-pound charge weight. Thus, the least square calculation was always based on three crater dimensions and sometimes on four crater dimensions. For each calculation of crater scaling parameters, that is, at each 0.1 scaled foot, one sigma limits were calculated for the scaling exponent and for the proportionality constants. A correlation coefficient was also calculated for each fit.

The scaled charge burst depth (at which crater scaling parameters were calculated) was determined by dividing actual burst depth by charge weight raised to an assumed power.

In addition to the calculations described above, a calculation was made to determine the apparent crater dimension scaling parameters using an iterative procedure. The result was a single exponent which could be used to scale both the crater dimension and charge burst depth. This iterative procedure for apparent crater radius and depth follows these steps:

1. Arbitrarily select a scaling exponent (such as 0.33) and using this exponent calculate the actual crater dimensions for each available depth-of-burst curve at the scaled burst depth of interest.
2. Using the actual crater dimensions calculated in step 1 above, determine the scaling intercept K and the scaling exponent b in the expression $DIM = KW^b$, where W is charge weight, and DIM is apparent crater radius or depth.
3. Compare the scaling exponent determined in step 2 above with that assumed in step 1. If they are not the same to the nearest 0.001 repeat the process assuming in step 1 of the scaling exponent calculated in step 2.
4. Repeat the above procedure until exponents satisfy the comparison test, continue to the next scaled burst depth and start again with step 1.

This iterative procedure for volume is the same as outlined above for radius or depth except that the charge depth scaling exponent is always one-third of the volume exponent. Again, all scaling calculations were made using the Method of Least Squares.

3.1 Playa

Apparent crater dimension crater scaling parameters for playa are based on depth-of-burst curves in Figures A.1 through A.8 of Appendix A. Figure 1 shows scaling exponent and intercept as a function of scaled burst depth for apparent crater dimensions using an arbitrarily chosen depth scaling exponent of 0.33.

Figure 1: APPARENT CRATER SCALING PARAMETERS FOR PLAYA - BURST DEPTH ARBITRARILY SCALED BY 0.33

The general shape of the scaling exponent curves (shown in Figure 1) are as would be expected after reviewing crater scaling data in References 1 - 4. The scaling exponent for crater radius is about 0.38 at the surface, decreases to about 0.30 at a scaled depth of 1.2 (ft/lb^{0.33}) and then increases slightly. The scaling exponent for depth is about 0.36 at the surface, decreases to about 0.26 at a scaled depth of 0.8 (ft/lb^{0.33}) and then increases significantly with deeper scaled burst depths. The scaling exponent for crater volume is about 1.12 at the surface, decreases to a value of about 0.85 at a scaled depth of 1.0 (ft/lb^{0.33}) and increases for deeper scaled burst depths. Vertical error bars reflected the greater scatter of crater dimensional data at the deeper burst depths.

Still referring to Figure 1 several interesting observations can be made. From dimensional analysis one expects that twice the radius exponent plus the depth exponent should be approximately equal to the volume exponent. Results of a check for this dimensional consistency are given in Table 1. The comparison is good.

Another correlation of some interest is that between the scaled burst depth at which the minimum scaling exponent occurred and the scaled burst depth observed from actual data at which the optimum crater dimensions occur. Results of such a correlation for playa are given in Table 2. Again, the correlation is quite good -- and one can conclude that scaling exponents reach a minimum at the scaled depth which roughly corresponds to that which results in maximum crater dimensions.

Table 1: CRATER RADIUS AND DEPTH EXPONENT COMPARED TO VOLUME EXPONENT -
CHARGE DEPTH SCALED BY CUBE ROOT

	Observed			$2 b_r + b_d$
	Radius Exponent (b_r)	Depth Exponent (b_d)	Volume Exponent	
Surface	0.38	0.36	1.12	1.14
At Minimum	0.30	0.26	0.85	0.86
$\lambda D_{ob} = 1.2 \text{ (ft/lb}^{0.33}\text{)}$	0.30	0.27	0.86	0.87
$\lambda D_{ob} = 0.8 \text{ (ft/lb}^{0.33}\text{)}$	0.31	0.26	0.88	0.88
$\lambda D_{ob} = 1.0 \text{ (ft/lb}^{0.33}\text{)}$	0.30	0.27	0.85	0.87

Note: Minimum values refer to minimum exponent observed for each crater dimension regardless of the scaled burst depth at which it occurred. Other sets are for a depth-of-burst at which only one exponent was a minimum. Radius was a minimum at a scaled burst depth of 1.2, depth at 0.8 and volume at 1.0

Table 2: COMPARISON OF SCALED BURST DEPTHS FOR MAXIMUM CRATER DIMENSIONS AND MINIMUM SCALING EXPONENTS

	Data			Minimum Exponents This Study
	8-Pound (Ref. 5)	64-Pound (Ref. 6)	256-Pound (Ref. 3)	
Radius	1.2	1.5	1.5+	1.2
Depth	0.85	0.87	0.83	0.80
Volume	1.05	1.00	0.96	1.00

Note: Scaled burst depths are $D_{ob}/\text{lb}^{0.33}$.

Although not included here, calculations similar to those illustrated in Figure 1 were made using arbitrarily chosen charge depths scaling exponents of 0.25 and 0.30. The results are summarized in Table 3. After a rather careful examination of these data, it is concluded that with regard to the one sigma limits and correlation coefficients the arbitrarily chosen burst depth exponent of 0.25 is best at least for the data given in Table 3. Again, the one sigma limits and the correlation coefficients reflect the large scatter of apparent crater data generally observed at the deeper burial depths.

Intercept values, that is, K in the scaling expression $DIM = KW^b$, are included in Figure 1 and Table 3. These values are included only to permit one to determine the scaling expression for a given burst depth if such is needed. Figures 2, 3 and 4 show apparent crater radius, depth and volume parameters, respectively, for a scaling exponent determined by the iterative procedure described in a previous section of this report. Convergence usually occurred after 5 to 6 iterations. For comparative purposes, selected scaling exponents with tolerances and one sigma limits are given in Table 4. The results are comparable to those for arbitrarily selected charge burst depth exponent (see Table 3). Again, the minimum crater dimension scaling exponent and the maximum crater dimension scaling intercept occur at a burst depth which roughly corresponds to that for which one would expect an optimum crater.

Table 3: Summary of Apparent Crater Scaling Exponents for Plava - Arbitrary
Burst Depth Scaling

	0.25	0.30	0.33	
RADIUS	Scaling Exponent at Surface (*)	0.380 ± .010 (.9987)	0.380 ± .010 (.9987)	0.380 ± .010 (.9987)
	Scaling Exponent at $D_{ob} = 1.0$ (*)	0.286 ± .007 (.9994)	0.296 ± .020 (.9956)	0.301 ± .029 (.9915)
	Scaling Exponent at Minimum (*) (**)	0.280 ± .026 (.9915) (1.4)	0.292 ± .036 (.9845) (1.3)	0.300 ± .041 (.9821) (1.2)
	Intercept at Surface (*)	0.661 $\begin{smallmatrix} + .043 \\ - .040 \end{smallmatrix}$ (.9987)	0.661 $\begin{smallmatrix} + .043 \\ - .040 \end{smallmatrix}$ (.9987)	0.661 $\begin{smallmatrix} + .043 \\ - .040 \end{smallmatrix}$ (.9987)
	Intercept at $D_{ob} = 1.0$ (*)	1.854 $\begin{smallmatrix} + .047 \\ - .054 \end{smallmatrix}$ (.9994)	1.909 $\begin{smallmatrix} + .162 \\ - .150 \end{smallmatrix}$ (.9956)	1.946 $\begin{smallmatrix} + .241 \\ - .213 \end{smallmatrix}$ (.9915)
DEPTH	Scaling Exponent at Surface (*)	0.356 ± .011 (.9980)	0.356 ± .011 (.9980)	0.356 ± .011 (.9980)
	Scaling Exponent at $D_{ob} = 1.0$ (*)	0.254 ± .012 (.9978)	0.271 ± .045 (.9729)	0.274 ± .078 (.9245)
	Scaling Exponent at Minimum (*) (**)	0.250 ± .011 (.9980) (0.8)	0.261 ± .010 (.9986) (0.8)	0.265 ± .028 (.9889) (0.8)
	Intercept at $D_{ob} = 1.0$ (*)	1.113 $\begin{smallmatrix} + .057 \\ - .054 \end{smallmatrix}$ (.9978)	1.080 $\begin{smallmatrix} + .224 \\ - .186 \end{smallmatrix}$ (.9729)	1.080 $\begin{smallmatrix} + .386 \\ - .302 \end{smallmatrix}$ (.9245)
	Intercept at Surface (*)	0.339 $\begin{smallmatrix} + .025 \\ - .024 \end{smallmatrix}$ (.9980)	0.339 $\begin{smallmatrix} + .025 \\ - .024 \end{smallmatrix}$ (.9980)	0.339 $\begin{smallmatrix} + .025 \\ - .024 \end{smallmatrix}$ (.9980)
VOLUME	Scaling Exponent at Surface (*)	1.125 ± .016 (.9958)	1.125 ± .016 (.9958)	1.125 ± .016 (.9958)
	Scaling Exponent at $D_{ob} = 1.0$ (*)	0.833 ± .094 (.9875)	0.849 ± .121 (.9799)	0.850 ± .157 (.9669)
	Scaling Exponent at Minimum (*) (**)	0.828 ± .101 (.9851) (1.1)	0.849 ± .121 (.9799) (1.0)	0.850 ± .157 (.9669) (1.0)
	Intercept at Surface (*)	0.200 $\begin{smallmatrix} + .031 \\ - .027 \end{smallmatrix}$ (.9992)	0.200 $\begin{smallmatrix} + .031 \\ - .027 \end{smallmatrix}$ (.9992)	0.200 $\begin{smallmatrix} + .031 \\ - .027 \end{smallmatrix}$ (.9992)
	Intercept at $D_{ob} = 1.0$ (*)	5.052 $\begin{smallmatrix} + 2.425 \\ - 1.638 \end{smallmatrix}$ (.9875)	5.408 $\begin{smallmatrix} + 3.576 \\ - 2.152 \end{smallmatrix}$ (.9799)	5.659 $\begin{smallmatrix} + 5.262 \\ - 2.727 \end{smallmatrix}$ (.9669)

* Correlation Coefficient

** Scaled burst depth (ft/lb^{0.33})

Figure 2: APPARENT CRATER RADIUS SCALING PARAMETERS FOR PLAYA - SCALING EXPONENT DETERMINED BY ITERATIVE PROCEDURE

Figure 3: APPARENT CRATER DEPTH SCALING PARAMETERS FOR PLAYA - SCALING EXPONENT DETERMINED BY ITERATIVE PROCEDURE

Table 4: APPARENT CRATER SCALING EXPONENTS FOR PLAYA---
DETERMINED BY ITERATIVE PROCEDURE

	Radius	Depth	Volume
Scaling Exponent at Surface (*)	0.380 ± 0.010 (0.9987)	0.356 ± 0.011 (0.9980)	1.125 ± 0.016 (0.9958)
Scaling Exponent at $\lambda_{Dob} = 0.5$ (*)	0.323 ± 0.004 (0.9997)	0.310 ± 0.012 (0.9972)	0.973 ± 0.030 (0.9981)
Scaling Exponent at $\lambda_{Dob} = 0.7$ (*)	0.308 ± 0.005 (0.9998)	0.301 ± 0.012 (0.9970)	0.948 ± 0.033 (0.9976)
Scaling Exponent at $\lambda_{Dob} = 1.1$ (*)	0.291 ± 0.022 (0.9942)	0.275 ± 0.046 (0.9731)	0.843 ± 0.0125 (0.9786)

* Correlation coefficient

NOTE: Exponents for surface craters are the same as given in Table 3.

Figure 4: APPARENT CRATER VOLUME SCALING PARAMETERS FOR PLAYA - SCALING EXPONENT DETERMINED BY ITERATIVE PROCEDURE

Again, it is of interest to investigate consistency of crater dimension exponents. Table 5 gives the results of this check for the iterative exponent data given in Figures 2, 3 and 4. The sum of twice the crater radius exponent plus the depth exponent compares quite well with the volume exponent.

Figure 5 shows apparent crater data for playa scaled using exponents determined from the iterative procedure. Also shown in Figure 5 are shaded regions indicating the data spread when cube root scaling is applied to both the crater dimension and the burst depth. No attempt has been made to fit a curve to these sets of data and to calculate the corresponding correlation coefficient. It appears, however, that a lesser data spread occurs when the iterative procedure is used. All plots of apparent crater scaling exponents exhibit the degraded correlation coefficients and the increased one sigma limits at the charge burst depths which are probably below that for maximum crater size. Actual data scatter is usually observed to be quite significant in the deep burst depth region. In an attempt to determine if these one sigma limits and correlation coefficients could be improved, the arbitrarily fitted smoothed curves were varied in the deep burst depth region for Air Vent crater radius and depth (see Figure A.5). Table 6 shows resulting exponents, one sigma limits and correlation coefficients for two values of scaled burst depth in the deep burst depth region. There is no significant improvement of correlation coefficient and one sigma limits due to this data manipulation.

Table 5: CRATER RADIUS AND DEPTH EXPONENT COMPARED TO
VOLUME EXPONENT - CHARGE DEPTH SCALED BY
ITERATIVE PROCEDURE

	Iterative Procedure			$2 b_r + b_d$
	Radius Exponent (b_r)	Depth Exponent (b_d)	Volume Exponent	
Surface	0.38	0.36	1.12	1.12
At Minimum	0.29	0.27	0.84	0.85
$\lambda_{Dob} = 1.2$	0.29	0.30	0.85	0.88
$\lambda_{Dob} = 1.0$	0.30	0.27	0.85	0.87
$\lambda_{Dob} = 1.1$	0.29	0.28	0.84	0.86

Note: Minimum values refer to minimum exponent obtained for each crater dimension regardless of scaled burst depth at which it occurred. Other sets are for depth-of-burst at which only one exponent was a minimum. Radius was a minimum at a scaled burst depth of , depth at , and volume at .

Table 6: COMPARISON OF CORRELATION COEFFICIENTS AND ONE
SIGMA LIMITS WHEN DATA CURVES ARE VARIED

Scaled Charge Burst Depth	Data Curve	Radius		Depth	
		Scaling Exponent	Correlation Coefficient	Scaling Exponent	Correlation Coefficient
1.2	Baseline	0.290±0.027	0.9909	0.300±0.098	0.9029
	Variation A	0.291±0.027	0.9913	0.303±0.101	0.8994
	Variation B	0.287±0.028	0.9903	0.296±0.095	0.9070
1.3	Baseline	0.290±0.034	0.9868	0.320±0.161	0.7984
	Variation A	0.291±0.033	0.9873	0.334±0.167	0.7957
	Variation B	0.285±0.035	9.9852	0.313±0.156	0.8000

Figure 5: APPARENT CRATER DIMENSIONS SCALED USING EXPONENTS DETERMINED FROM ITERATIVE PROCEDURE

3.2 Desert Alluvium

Apparent crater scaling parameters (exponent and intercept) as a function of scaled burst depth using arbitrarily chosen scaling exponent for burst depth of 0.33 are given in Figure 6. Data given in this figure is based on smoothed burst depth curves shown in Appendix A, Figures A.9 through A.18. The arbitrarily chosen exponent for scaled burst depth used in Figure 6 is 0.30.

In studying Figure 6, it should be noted that the only complete depth of burst data curve is that for 256-pound charges (see Figure A.9 and A.10). Other data curves are either for a limited portion of the depth-of-burst range or the entire depth-of-burst range is covered with few data. In this regard, the data for playa is more complete than that for desert alluvium. Note in Figure 6 that a significant portion of the curve is dashed. For this dashed section only data curves for two charge weights were available for crater scaling calculations.

Scaling exponent plots shown in Figure 6 tend to vary in a way opposite from those observed for playa. The scaling exponent plots for playa exhibit an upper value at the surface, decrease to a minimum roughly corresponding to the scaled charge burst depth at which an optimum crater is formed, and then increase at great depths. Here for desert alluvium, the scaling exponent is at a lower value at the surface and increases with increasing scaled depth-of-burst.

The surface scaling exponent for each crater dimension seems low; that is, approximately 0.24 for radius, 0.28 for depth and 0.80 for volume. One

Figure 6: APPARENT CRATER SCALING PARAMETERS FOR DESERT ALLUVIUM--- BURST DEPTH ARBITRARILY SCALED BY 0.30

would expect the exponent for radius and depth to be on the order of 0.33 and volume about 1.0. Recalculated surface scaling exponents without the nuclear crater data (Figures A.17 and A.18) results in values of approximately 0.27 for radius, 0.30 for depth and 0.88 for volume. This increases these exponents slightly but they still are significantly lower than expected. The question regarding crater scaling exponents at the surface for desert alluvium cannot be resolved without additional data.

Figures 7 and 8 show apparent crater radius and depth scaling parameters, respectively, for a scaling exponent determined by the iterative procedure described in a previous section of this report. Again, the curves shown in Figures 7 and 8 are limited because of lack of data. Dashed portions of these curves are based on smoothed curves for only two charge weights. Convergence generally resulted after 5 or 6 iterations. When comparing one sigma limits and correlation coefficients to those exhibited in Figure 6, one observes that iterative values are equivalent or better in almost every case.

3.3 Basalt

Apparent crater scaling parameters (exponent and intercept) as a function of scaled burst depth using an arbitrarily selected scaling exponent for charge depth of 0.33 are given in Figure 9. Data shown in Figure 9 are based on smoothed burst depth curves given in Appendix A, Figures A.19 through A.30.

Figure 7: APPARENT CRATER RADIUS PARAMETERS FOR DESERT ALLUVIUM---
SCALING EXPONENT DETERMINE BY ITERATIVE PROCEDURE

Scaling Exponent

Intercept

Figure 8: APPARENT CRATER DEPTH PARAMETERS FOR DESERT ALLUVIUM---
SCALING EXPONENT DETERMINED BY ITERATIVE PROCEDURE

Figure 9: APPARENT CRATER SCALING PARAMETERS FOR BASALT---BURST DEPTH ARBITRARILY SCALED BY 0.33

Basalt is included here only because it is a rock medium. Basalt data exhibit high scatter. There is no complete burst depth curve for a given yield, rather a series of short burst depth segments are available. Other difficulties with these data include differing charge shapes (spheres and cylinders), differing explosive types, and the extreme data scatter which is always observed for small high-explosive crater data in rock media. Reference to Figures A.19 through A.30 will give an indication of the difficulties encountered in attempting to fit a smooth depth of burst curve through the basalt data. The erratic nature of the data is reflected in large one sigma limits and rather poor correlation coefficients for these basalt crater scaling calculations.

Note in Figure 9 that there is a definite tendency for scaling exponent to exhibit a lower value at the surface, increase to a maximum with increasing burst depth and then decreases. This is a scaling exponent dependence on charge burst depth similar to that observed for desert alluvium. For apparent crater radius and depth the intercept continues to increase with charge burst depth from an initial low value at the surface without reaching a maximum.

Crater parameter depth of burst calculations were also made without the cylindrical, pelletized TNT explosive data for the Canal Zone basalt. This did not improve the tolerance limits, correlation coefficients or curve shapes significantly over those shown in Figure 9.

Figures 10 and 11 show apparent crater radius and depth scaling parameters, respectively, for a scaling exponent determined by the iterative procedure

Figure 10: APPARENT CRATER RADIUS SCALING PARAMETERS FOR BASALT---
SCALING EXPONENT DETERMINED BY ITERATIVE PROCEDURE

Figure 11: APPARENT CRATER DEPTH SCALING PARAMETERS FOR BASALT---
SCALING EXPONENT DETERMINED BY ITERATIVE PROCEDURE

described in a previous section of this report. As mentioned above, the large variation on the one sigma limits and the lower values of the correlation coefficient are due of course to the poor quality and scarcity of crater burst depth data for basalt. Comments regarding the shape of the scaling exponent and intercept curves are similar to those made for data shown in Figure 9.

4.0 DISCUSSION

The empirical study described here demonstrates the dependence of crater scaling parameters on charge burst depth. It appears that apparent crater scaling parameters change smoothly as the explosive charge burst depth is increased.

Regarding the variation of the apparent crater dimension scaling exponent with charge burst depth, that observed for playa is consistent with the conclusions drawn by others investigating explosive craters in soil. It should be noted, however, that these other investigations were mainly concerned with craters in desert alluvium. The variation of the apparent crater dimension scaling exponent with charge burst depth observed here for desert alluvium is not consistent with conclusions drawn by other investigators. (See References 1, 2, 3 and 4.)

Correlations for playa are better than those for desert alluvium and basalt because cratering depth-of-burst data are more complete for playa. Cratering data for basalt exhibit much more scatter than that exhibited by playa and desert alluvium. Thus, the construction of smoothed burst depth curves through these basalt data required much judgment -- and was more difficult than constructing curves through the desert alluvium and playa cratering data. It should be noted that crater scaling relationships calculated for playa was based on four charge weights at scaled burst depths less than optimum from a cratering standpoint. These relationships were generally based on two and three charge weights for basalt and desert alluvium.

This study shows a difference in functional dependence of apparent crater scaling parameters on charge burst depth for the three types of geologic media included here. The data are poor, however, for basalt and sparse for desert alluvium, so one cannot consider the indicated functional relationship conclusive.

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5.0 CONCLUSIONS

1. Based on this empirical analysis, crater scaling parameters for playa, desert alluvium and basalt appear to vary directly and smoothly with charge burst depth.
2. The crater scaling exponent from apparent crater dimensions in playa reaches a minimum at a scaled burst depth which is roughly equal to that which produces an optimum apparent crater.
3. An iterative procedure for determining crater dimensions scaling exponent results in scaling parameter burst depth curves which are equivalent to or better than those which result when burst depth exponent is arbitrarily selected.

6.0 RECOMMENDATIONS

Plan future experiments in soil and rock to yield complete apparent crater burst depth curves for several (at least 4) charge weights. These data will permit the empirical determination of complete burst depth curves for crater scaling parameters.

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APPENDIX A - APPARENT CRATER DATA

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Table A.1: APPARENT CRATER DIMENSIONS FOR 8-POUND
EVENTS IN PLAYA

Shot No.	Weight (lb)	of Burst (ft)	Crater Dimensions		
			Radius (ft)	Depth (ft)	Volume (ft ³)
E1a	8	0	1.55	0.91	2.33
E1b	8	0	1.47	0.67	1.76
E1c	8	0	1.31	0.65	1.54
E2a	8	0.5	2.54	1.11	11.55
E2b	8	0.5	2.25	1.06	8.00
E2c	8	0.5	2.43	1.44	11.56
E3a	8	1.0	2.78	1.60	15.69
E3b	8	1.0	3.02	1.54	17.03
E3c	8	1.0	2.70	1.75	15.68
E3.5a	8	1.5	2.85	1.71	18.1
E4a	8	2.0	3.43	1.77	26.64
E4b	8	2.0	3.56	1.94	34.32
E4c	8	2.0	3.68	1.81	36.37
E4.5a	8	2.5	3.75	1.48	27.4
E4.5b	8	2.5	3.31	1.01	13.0
E5a	8	3.0	3.68	0.80	16.82
E5b	8	3.0	4.00	1.79	38.7
E5c	8	3.0	3.66	0.67	13.72
E5.5a	8	3.5	3.16	0.34	7.05
E6a	8	4.0	1.90	0.20	1.24
E6b	8	4.0	1.50	0.12	0.52
E6c	8	4.0	2.40	0.11	2.22

Table A.2: APPARENT CRATER DIMENSIONS FOR 64-POUND
EVENTS IN PLAYA

Shot No.	Charge Weight (lb)	Depth of Burst (ft)	Crater Dimensions		
			Radius (ft)	Depth (ft)	Volume (ft ³)
211-53	64	0	3.2	1.5	20.3
211-51	64	0	3.6	1.6	25.7
211-40	64	4	7.3	4.2	260
211-47	64	5	8.0	3.8	326
211-48	64	6	8.4	4.2	369
211-49	64	7	7.7	3.0	206

Table A.3: APPARENT CRATER DIMENSIONS FOR 256-POUND
AIR VENT EVENTS IN PLAYA

Shot No.	Charge Weight (lb)	Depth of Burst (ft)	Crater Dimensions		
			Radius (ft)	Depth (ft)	Volume (ft ³)
II-1	256	-0.865	3.20	0.82	13.13
II-2A	256	0	5.54	2.39	95.46
II-2B	256	0	5.40	2.43	93.22
II-3	256	0.865	6.72	3.38	235.4
II-4	256	1.59	7.62	3.72	247.0
II-5A	256	3.175	8.84	4.13	426.0
II-5B	256	3.175	8.50	4.35	381.0
II-6	256	4.76	9.58	4.64	517.0
II-7A	256	6.35	9.82	4.36	505.7
II-7B	256	6.35	9.94	4.49	544.0
II-8	256	7.94	10.32	3.98	483.0
II-9A	256	9.53	10.98	3.63	486.0
II-9B	256	9.53	11.02	2.34	332.0

Table A.4: APPARENT CRATER DIMENSIONS FOR 20-TON
CRATERING EVENTS IN PLAYA

Shot No.	Charge Weight (lb)	Depth of Burst (ft)	Apparent Crater Dimensions		
			Radius (ft)	Max Depth (ft)	Volume (ft ³)
AIR VENT Phase I	40,000	17.19	47.61	22.5	7.25x10 ⁴
FLAT TOP II	40,000	0	35.0	12.1	23,200
FLAT TOP III	40,000	0	38.8	18.5	38,200

Table A.5: 256-POUND CRATERING EVENTS IN DESERT ALLUVIUM

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			Reference
		Radius (ft)	Depth (ft)	Volume (ft ³)	
207	-0.83	4.05	1.40	37.0	1
206	0	6.35	1.70	129	1
S2-12	0	8.57	2.49	161	2
S2-13	0	8.34	2.60	267	2
205	0.83	8.90	2.20	312	1
403	0.83	8.36	3.37	301	1
204	1.65	9.35	2.40	363.6	1
405	1.65	9.24	4.60	511	1
401	3.17	10.6	5.45	837	1
203	3.17	8.35	4.10	358	1
406	3.17	9.95	4.22	686	1
402	4.76	11.05	6.25	961	1
S1-8	6.35	13.13	7.3	1,489	2
404	6.35	12.10	6.12	1,195	1
212	6.35	11.2	6.07	1,174	1
202	6.35	11.4	5.90	1,027	1
S1-2	9.53	15.12	7.86	2,146	2
S1-9	9.53	14.14	7.16	1,930	2
S1-10	12.7	13.4	4.1	1,093	2
S1-16	12.7	14.19	6.7	2,220	2
S2-11	13.10	14.69	5.43	1,670	2
S1-4	15.90	11.32	1.77	368	2
S1-11	15.90	6.53	3.80	236	2
S2-10	16.10	14.10	4.55	1,077	2
S2-9	16.40	14.29	2.61	716	2
S2-8	19.0	10.07	1.60	297	2
S1-12	19.05	9.36	2.30	256	2
S1-17	19.05	5.68	1.70	55.0	2
S2-7	19.7	8.13	1.01	121	2
S2-6	22.6	4.39	1.00	170	2
S2-5	23.3	3.03	0.30	17.9	2
S1-15	25.4	4.18	0.45	31.0	2
S2-4	25.5	2.35	1.15	16.4	2

Table A.6: 1,000-POUND CRATERING EVENTS IN DESERT ALLUVIUM

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			Reference
		Radius (ft)	Depth (ft)	Volume (ft ³)	
PR B-1 (1006)	15.0	21.0	9.7	6,561	4
PR B-2 (1005)	16.6	21.8	9.1	7,560	4
PR B-3 (1009)	18.2	20.9	7.8	5,832	4
PR B-4 (1009)	19.8	20.5	9.5	6,534	4
PR B-5 (1014)	21.4	19.7	4.1	2,646	4
PR B-6 (1016)	19.6	20.7	8.3	6,075	4
PR F-1 (1000)	19.8	22.7	11.8	7,860	4
PR F-2 (1000)	19.8	21.2	9.8	6,030	4
PR F-3 (1000)	18.33	21.1	11.0	6,950	4
PR F-4 (1000)	18.5	22.1	10.8	7,560	4
PR B-T (1017)	15.0	22.7	10.9	---	4

Table A.7: 2,560-POUND CRATERING EVENTS IN DESERT ALLUVIUM

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			Reference
		Radius (ft)	Depth (ft)	Volume (ft ³)	
HE 4	-2.05	6.9	1.9	110	21
HE 1	2.05	18.5	6.7	2,010	21
HE 5	4.10	19.4	7.5	4,000	3
HE 6	3.01	19.8	6.1	3,600	3
HE 7	2.6	19.0	6.7	3,300	3
HE 3	6.84	20.27	10.8	6,000	21

Table A.8: 20-TON CRATERING EVENTS IN DESERT ALLUVIUM

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			Reference
		Radius (ft)	Depth (ft)	Volume (ft ³)	
HE 2	5.13	39.0	15.0	35,000	21
ST-2	17.1	50.5	23.6	83,600	6
ST-3	34.2	58.6	29.2	144,600	6
ST-1	80.0	57.0	7.9	49,100	6

Table A.9: 1.2-KILOTON NUCLEAR CRATERING EVENTS IN DESERT ALLUVIUM

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			Reference
		Radius (ft)	Depth (ft)	Volume (ft ³)	
Jangle S	-3.48	45.0	19.0	49,300	23
Jangle U	17.0	130.0	53.0	973,000	23
Teapot ESS	67.0	146.0	90.0	2.6x10 ⁶	20

Table A.10: 25-POUND CRATERING EVENTS IN BASALT

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			Reference
		Radius (ft)	Depth (ft)	Volume (ft ³)	
14	0.0	2.02	0.73	5.7	11
13	1.5	4.59	3.05	85.6	11
9	3.0	2.38	1.20	11.3	11
6	4.5	2.92	0.85	16.7	11
4	6.0	6.64	2.90	98.8	11
7	9.0	3.52	2.30	14.3	11
10	10.5	1.89	0.63	1.6	11

Table A.11: 75-POUND CRATERING EVENTS IN BASALT

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			Reference
		Radius (ft)	Depth (ft)	Volume (ft ³)	
2	4.0	3.49	0.70	34.6	11
3	6.0	6.92	3.43	21.1	11

Table A.12: 200-POUND CRATERING EVENTS IN BASALT

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			Reference
		Radius (ft)	Depth (ft)	Volume (ft ³)	
15(1A)	0.0	4.65	1.6	49.4	11
16(2A)	0.0	5.3	1.2	62.9	11
17(3A)	1.2	5.55	1.3	43.2	11
18(4A)	1.2	3.70	1.1	30.0	11
12	12.0	9.52	3.98	547	11

Table A.13: 1,000-POUND CRATERING EVENTS IN BASALT

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			Reference
		Radius (ft)	Depth (ft)	Volume (ft ³)	
BK-2	18.9	4.63	1.4	44.9	12
BK-3	14.7	15.65	5.2	1,800	12
BK-4	9.6	16.7	6.5	2,620	12
BK-5	4.8	15.0	7.5	1,890	12
BK-6	24.0	6.1	5.2	185	12
BK-7	18.6	10.67	3.8	654	12
BK-8	14.7	16.92	8.8	3,500	12
BK-9	9.6	12.15	4.8	800	12
BK-10	4.8	15.8	7.0	2,660	12

Table A.14: 4,000-POUND MTCE CRATERING EVENTS IN BASALT

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			References
		Radius (ft)	Depth (ft)	Volume (ft ³)	
S1(C1)	0.0	12.1	3.4(3.6)	733	1
S2a	0.0	10.7	3.9(4.0)	672	1
S3a	0.0	11.4	4.0(4.0)	853	1
S4a	0.0	10.4	3.1(4.0)	605	1
ST 1	-2.2	3.7	1.0(1.3)	37	1
ST2a	-2.2	6.8	1.4(1.9)	139	1
ST3a(C3)	-2.2	4.5	0.9(1.2)	25	1
C2	2.2	14.0	4.6(5.3)	1,500	1
16,000-Pound MTCE Event					
LS	0.0	18.7	5.4(5.6)	3,659	1
64-Pound OSO Events					
OSO1	0.0	3.8	1.4	36.2	2
OSO2	0.0	4.7	1.6	55.8	2

Table A.15: 20-TON CRATERING EVENTS IN BASALT

Shot No.	Depth of Burst (ft)	Apparent Crater Dimensions			Reference
		Radius (ft)	Depth (ft)	Volume (ft ³)	
BK-11	25.5	44.66	24.9	54,220	12
BK-12	42.7	57.0	34.7	135,000	12
BK-13	58.8	36.8	16.2	23,200	12
Alpha	58.4	50.3	22.9	75,800	13
Bravo	50.6	49.0	25.5	73,900	13
Delta	42.7	46.1	25.6	64,900	13

Figure A.1: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 8-POUND CHARGES IN PLAYA

Figure A.2: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 8-POUND CHARGES IN PLAYA

Figure A.3: APPARENT CRATER RADIUS AND CHARGE DEPTH AS A FUNCTION OF BURST DEPTH FOR 64-POUND CHARGES IN PLAYA

Figure A.4: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 64-POUND CHARGES IN PLAYA

Figure A.5: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 256-POUND CHARGES IN PLAYA

Figure A.6: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 256-POUND CHARGES IN PLAYA

Figure A.7: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 20-TON CHARGES IN PLAYA

Figure A.8: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 20-TON CHARGES IN PLAYA

Figure A.9: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 256-POUND CHARGES IN DESERT ALLUVIUM

Figure A.10: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH
FOR 256-POUND CHARGES IN DESERT ALLUVIUM

Figure A.11: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 1,000-POUND CHARGES IN DESERT ALLUVIUM

Figure A.12: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 1,000-POUND CHARGES IN DESERT ALLUVIUM

Figure A.13:

APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 2,560-POUND CHARGES IN DESERT ALLUVIUM

Figure A.14:

APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 2,560-POUND CHARGES IN DESERT ALLUVIUM

Figure A.15: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 20-TON CHARGES IN DESERT ALLUVIUM

Figure A.16: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 20-TON CHARGES IN DESERT ALLUVIUM

Figure A.17: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 1.2 KILOTON NUCLEAR CHARGES IN DESERT ALLUVIUM

Figure A.18: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 1.2 KILOTON NUCLEAR CHARGES IN DESERT ALLUVIUM

Figure A.19: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 25-POUND CHARGES IN BASALT

Figure A.20: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 25-POUND CHARGES IN BASALT

Figure A.21: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 75-POUND CHARGES IN BASALT

Figure A.22: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 75-POUND CHARGES IN BASALT

Figure A.23: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 200-POUND CHARGES IN BASALT

Figure A.24: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 200-POUND CHARGES IN BASALT

Figure A.25: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 1,000-POUND CHARGES IN BASALT

Figure A.26: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 1,000-POUND CHARGES IN BASALT

Figure A.27: APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 4,000-POUND CHARGES IN BASALT

Figure A.28: APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 4,000-POUND CHARGES IN BASALT

Figure A.29:

APPARENT CRATER RADIUS AND DEPTH AS A FUNCTION OF BURST DEPTH FOR 20-TON CHARGES IN BASALT

Figure A.30:

APPARENT CRATER VOLUME AS A FUNCTION OF BURST DEPTH FOR 20-TON CHARGES IN BASALT