TECHNICAL NOTE R-197

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COMPUTATION OF DEBRIS PROBLEM CAUSED BY ACTIVE SEISMIC SHOTS ON THE LUNAR SURFACE

by Charles Broder

May 1966

RESEARCH LABORATORIES
BROWN ENGINEERING COMPANY, INC.
HUNTSVILLE, ALABAMA

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COMPUTATION OF DEBRIS PROBLEM CAUSED BY ACTIVE SEISMIC SHOTS ON THE LUNAR SURFACE

May 1966

Prepared For

NUCLEAR AND PLASMA PHYSICS BRANCH
RESEARCH PROJECTS LABORATORY
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By

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Charles Broder

ABSTRACT

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This report determines impact densities and velocity distribution of the debris resulting from explosions on the lunar surface. Consideration is given to the type of soil that will give the best empirical data. Crater volumes and shapes are predicted, and the ejecta patterns determined are based on radial ejection of material from the charge center.

Author

Approved:

J. E. White, Jr.
J. E. White, Jr.
Research Projects Coordinator

Approved:

RC Watson
R. C. Watson, Jr.
Vice President
Advanced Systems and Technologies

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF SYMBOLS

A	Empirical constant determined by velocity curve fit
D	Crater depth
D_c	Charge depth measured to the center of mass
D_p	Initial depth of particle
d	Distance from a point to the charge center
g	Acceleration due to lunar gravity
k	Empirical constant
m	Empirical constant
n	Empirical constant determined by velocity data
R	Crater radius
R_b	Ballistic range
R_g	Ground range from the center of the crater
ΔR	Change in ground range associated with $\Delta \theta$
r_i	Initial ground range
V	Crater volume
v	Exit velocity at the surface
v_{max}	The maximum velocity a particle can have as a result of a given charge weight and burial depth. It is associated with vertical ejection.
W	Charge weight

θ	Ejection angle measured with horizontal
θ_{min}	Smallest ejection angle possible
$\Delta\theta$	Decrementing angle in computer program
λ	Depth of burst using cube-root scaling
ρ	Lunar surface density
τ	Empirical constant
χ_e	Epicenter depth

INTRODUCTION

If explosions are used on the Moon to perform active seismic experiments, a problem may arise that is not generally of concern when performing similar experiments on Earth. Because of the Moon's weaker gravitational field and the lack of appreciable atmospheric drag, particles ejected from the surface due to an explosion may have long trajectories.

A study to determine the seriousness of this problem was initiated by the Nuclear and Plasma Physics Branch of the Research Projects Laboratory of Marshall Space Flight Center. The objectives are to

- Investigate the velocity distribution of particles resulting from explosions
- Compute impact density distribution on the lunar surface.

In order to fulfill these objectives, the nature of the soil and the size and the depth of the charges must be considered. Included is a discussion of how to find the amount of ejecta and what the velocity distribution might be upon explosion. The equation for the velocity variation for each point in the crater is presented, and the range of the particles is determined.

A discussion of the computer program is also presented. This program finds the mass and velocity for all ground ranges.

The author wishes to acknowledge the contribution of Hal L. Cronkhite, who wrote the computer program.

DISCUSSION

THE LUNAR SURFACE

A search of the literature dealing with the nature of the Moon's surface yields little that is conclusive. There are a variety of descriptions which are often contradictory. The only fact that seems to be universally accepted is that there is a layer of fine dust at the top surface. Most estimates of its depth range between 0. 1 millimeter to over a meter.

The near surface layer of the Moon probably consists of a frothy, porous or pumice-like rock. This statement is based on the fact that many lunar surface characteristics can be simulated by a dendriform material of low bulk density. Estimates of its thickness range over the spectrum of values from one centimeter to several meters. This material is not piled dust or powder but resembles a slag-like mass[1]. Salisbury[2] discusses a rubble layer that is 63 centimeters to 1 meter thick. He states that it is locally absent in the intercrater areas and averages less than 1 meter in depth, but may be 15 meters around rims of craters. He surmises a 275-meter thickness of this rubble in highland areas. If the surface is dust, several kilometers thick, the material would not have to maintain the consistency of a fine powder, but would probably be in various stages of cementation[3]. It will thus be assumed that the surface consists of a granular layer of variable depth, overlaying a solid mass. Although some have conjectured that the depth is much greater, there is not any reasonable evidence at the present time to indicate that there is a layer of more than a few millimeters which maintains the properties of a fine loose dust. The recent Luna IX photographs indicate this might be the case. One of them is presented in Figure 1.

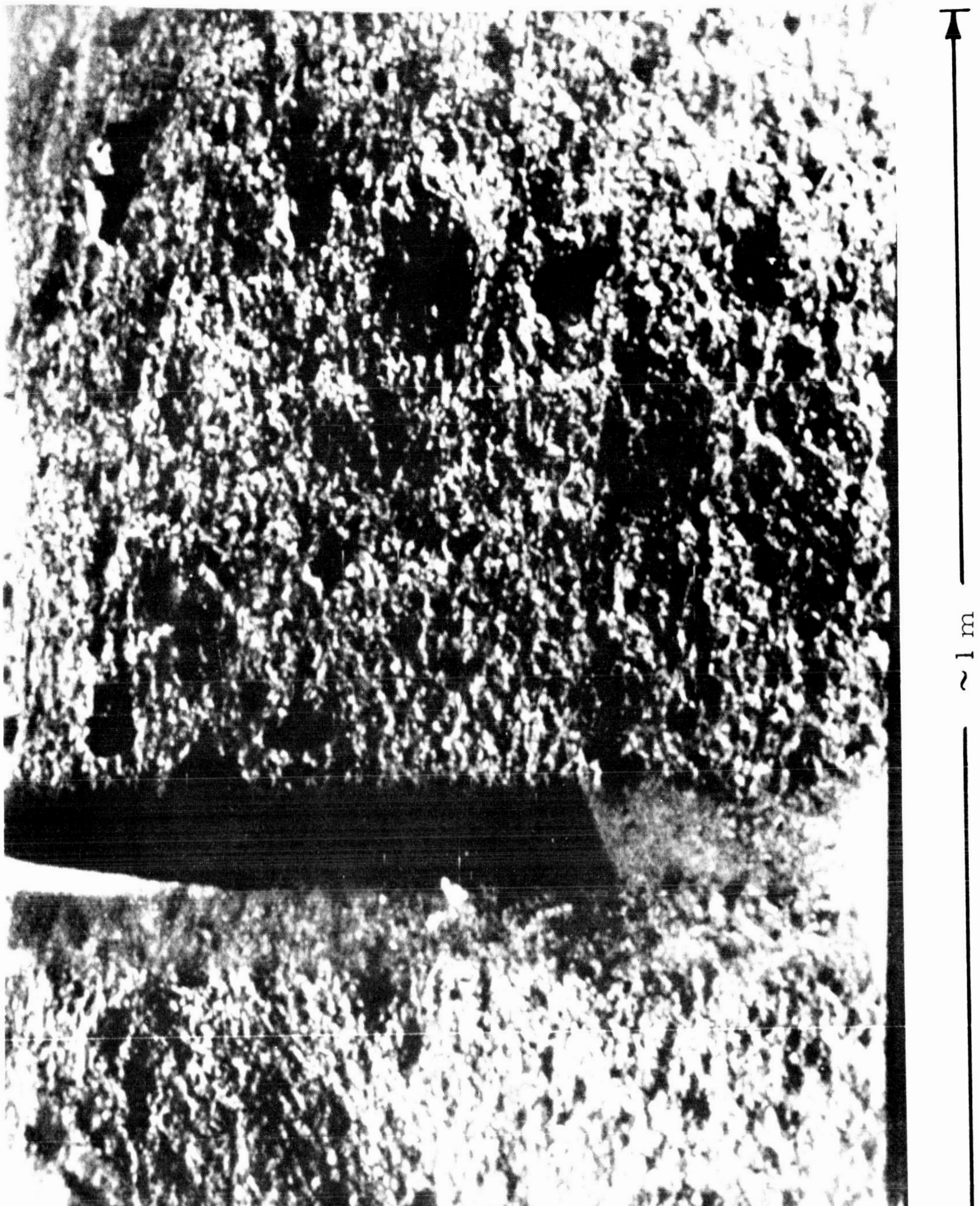


Figure 1. Surface of the Moon as Shown in a Luna IX Photograph

EXPLOSIVE SIZE

The scope of this report will be limited to chemical explosives that are below two hundred and sixty pounds in weight. This range should include all explosives used on the Moon in the course of the next few years since the major use for explosives on the first few lunar trips will be for seismic tests. On the Earth, typical explosive weights for reflection readings in an area such as the Gulf Coast are 1 to 10 pounds buried thirty feet, and 80 pounds for air shots. Refraction test explosives can be buried 100 feet and weigh 100 to 300 pounds, but the heavier the explosive is, the less efficient it becomes since a greater proportion of energy goes into shattering the rock and not into elastic waves. The Moon has a lower background noise level than does the Earth, so a one-pound charge should be sufficient for a seismic profile.[4] Based on Earth field studies of volcanic and igneous rock, Cramblit[5] also feels that one pound is more than adequate.

EJECTA VOLUME

In order to determine quantitative values for the energy and velocity flux of the ejected particles immediately after explosion, it is necessary to deal with some uncertainties and inseparable variables.[5] With a complete knowledge of energy conversion for a specific explosion, shock wave theory and lunar soil properties (which would include cohesiveness, rate of surface erosion and density), it might be theoretically possible to calculate the force on a particle at any point at a given instant in time. It must be realized, however, that since each particle is in motion, the velocity and acceleration on the particle will be a function of time. Cramblit[5] states, "A pure mathematical solution is not possible because the variable particle velocity factor cannot be separated in an equation from other time-dependent variables. Thus most blast effect equations on Earth are based on empirical relations determined by fitting curves to computed blast data".

The amount of ejecta material that can be expected to result from a given explosion is not equal to the amount that appears to be missing, judging by the crater's size. Allowance must be made for fallback and compaction of material. A true crater can only be viewed when all loose soil and fallback is removed. Ejecta then usually accounts for 40 to 55 percent of the crater's volume[6]. The exact amount varies with the charge burial depth, but there is a maximum to this variation.

The apparent crater is the crater that is measured before loose rubble is cleared. The rubble includes fallback. Carlson and Jones[6] found that ejecta accounted for about 88 percent of the missing crater mass when subsurface explosions were detonated and about 60 percent for surface shots. The soil in which their testing took place was lake playa. The charge weighed 256 lb, and the scaled charge burial depth (λ) ranged between 0 and 1-1/2 ft.

A word should be said about the units that will be used. Scaled burial depth is simply the depth of the center of mass of the charge divided by the cube root of the charge weight. Scaled crater volume is the volume divided by the charge weight. Caution is necessary when working with scaled units. Sachs and Swift[7] found that with the exception of airblast phenomena, different size TNT explosions in the same soil did not strictly obey $W^{\frac{1}{3}}$ model laws. The degree of variation was dependent on the soil characteristics and the physical quantity being considered. The heavier charges tended to produce scaled volumes that were larger than those of lighter charges. In the range of weights that will be considered, this problem need not be of concern.

Figure 2 shows how the scaled crater radius and depth vary with charge burial depth. Figure 3 shows the measured values of apparent crater volumes and a curve labeled "computed volume". The value of the computed volume for each specific charge depth is the volume of a cone whose height and radius correspond to the crater depth and radius values.

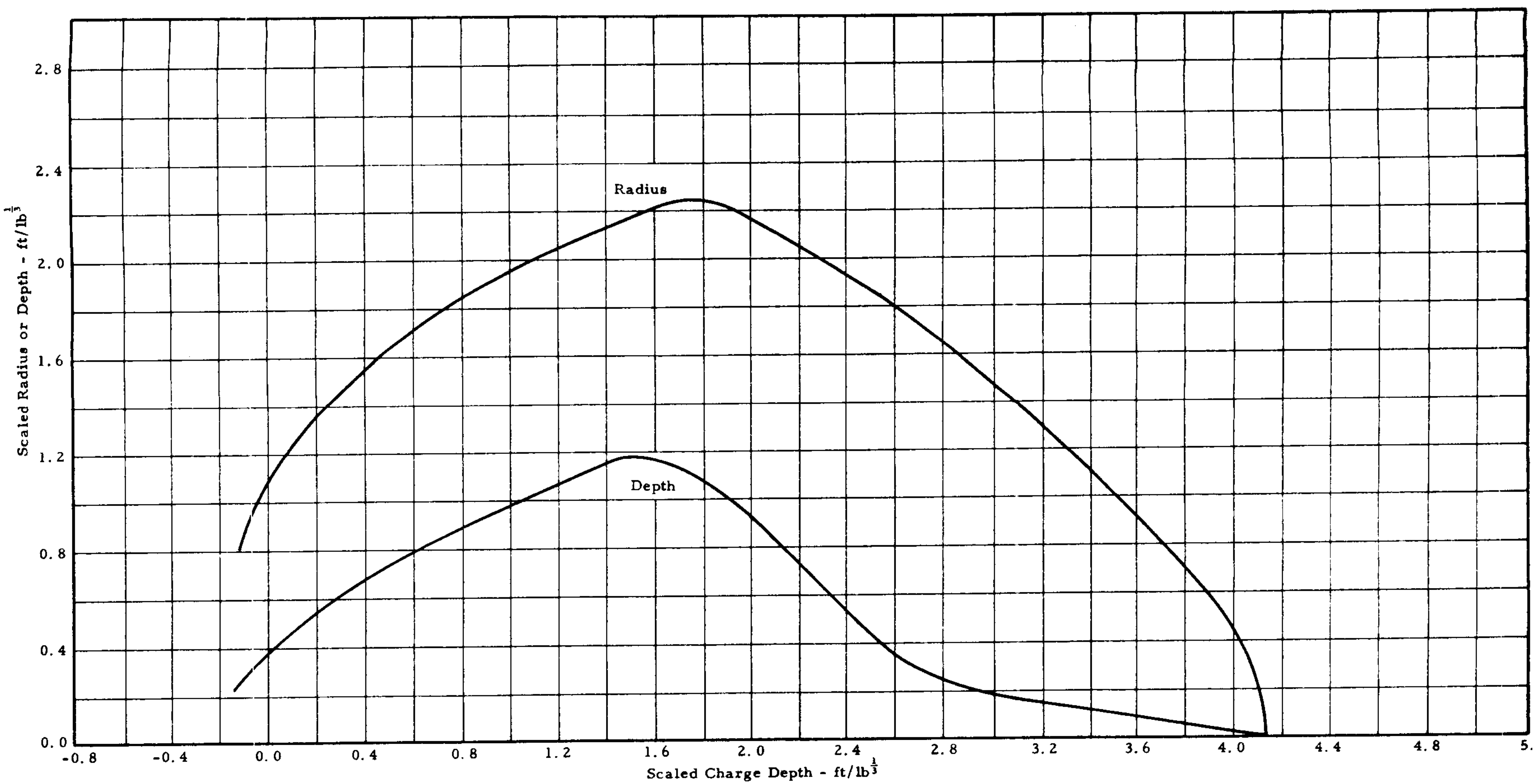


Figure 2. Scaled Crater Radius and Depth as a Function of Scaled Charge Depth in Desert Alluvium (References 7, 8 and 9)

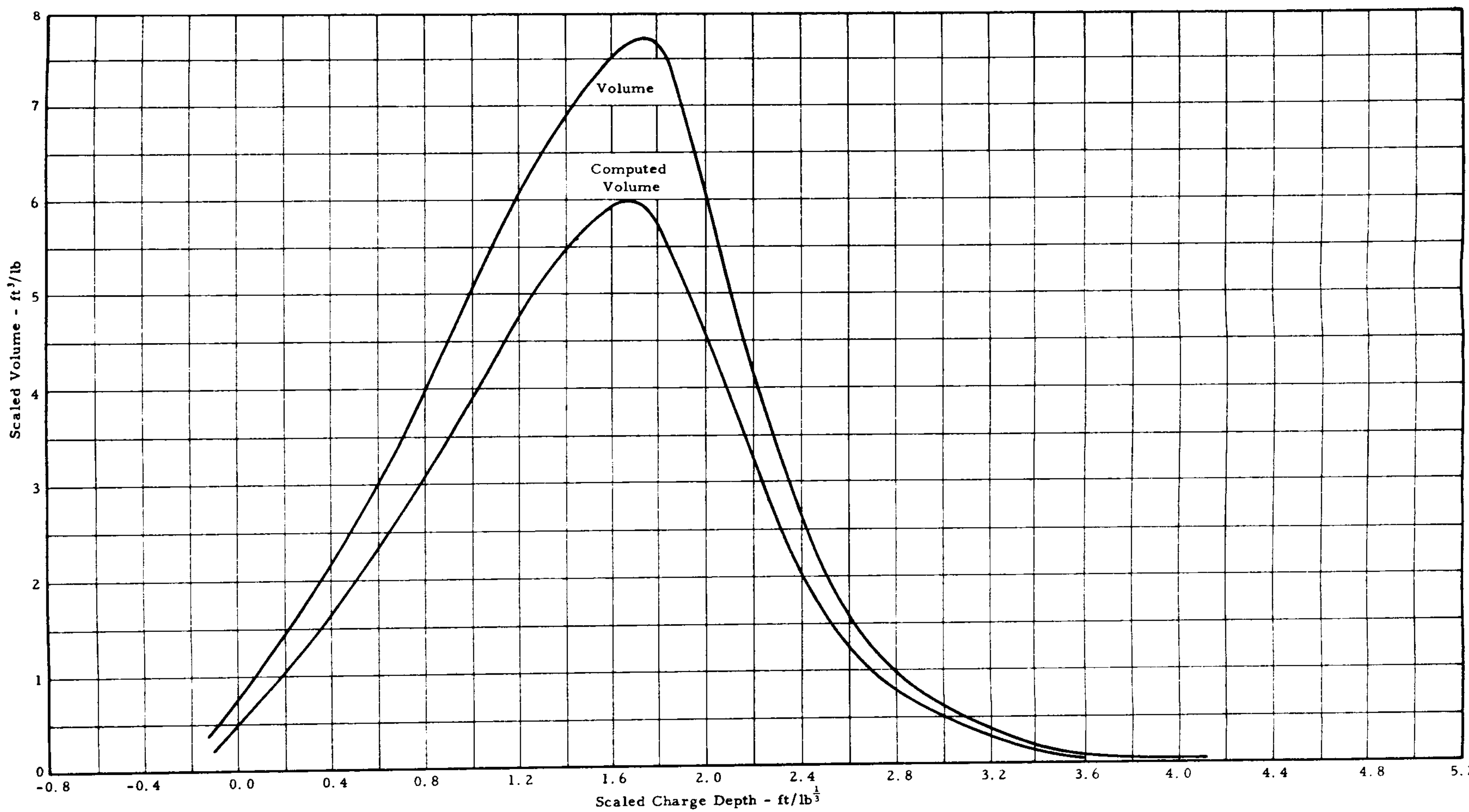


Figure 3. Scaled Crater Volumes as a Function of Scaled Charge Depth in Desert Alluvium (References 7, 8 and 9)

If the proper allowance is made for the fact that the amount of ejecta is actually less than the measured crater volume, then the computed crater volume approximates the ejecta volume to within 10 percent. The computer program that calculates the areal density of the ejecta spray uses conical volumes to determine the mass ejected from craters. Proper values are extracted from the curves in Figure 2 .

The amount of ejecta from a lunar crater can only be approximated by using Earth data for soil types that are assumed to be similar to lunar soil. The amount of ejecta is, however, much more dependent upon the burial depth of the charge than on the soil composition. Crater profile predictions are more reliable for deeper shots, and the radius profile reproduces better than the depth. Mildly cohesive soil damps air-to-earth disturbances better than strongly cohesive dry clay[7]. It should be recognized that little is known about the material that lies just beneath the thin surface layer; the results herein may have to be modified and different soils might even have to be considered as our knowledge of the lunar surface increases.

Figures 4 and 5 present crater depth and radii for various soils, charge sizes and charge burial depths. The three curves that show the largest radii were taken from true craters rather than apparent craters; but since the major difference between the two craters is the exclusion of fallback volume, the value of the radius should not change much between the two types of measurements taken. The curves show the trend for an increase in the radius as the charge is buried deeper. A maximum radius exists; after this radius is reached, the deeper the charge is buried, the smaller the radius becomes. Finally the charge is buried so deep that no crater appears at the surface.

The radius and depth are also dependent on the moisture content of the soil. As the amount of moisture increases, both will usually increase.

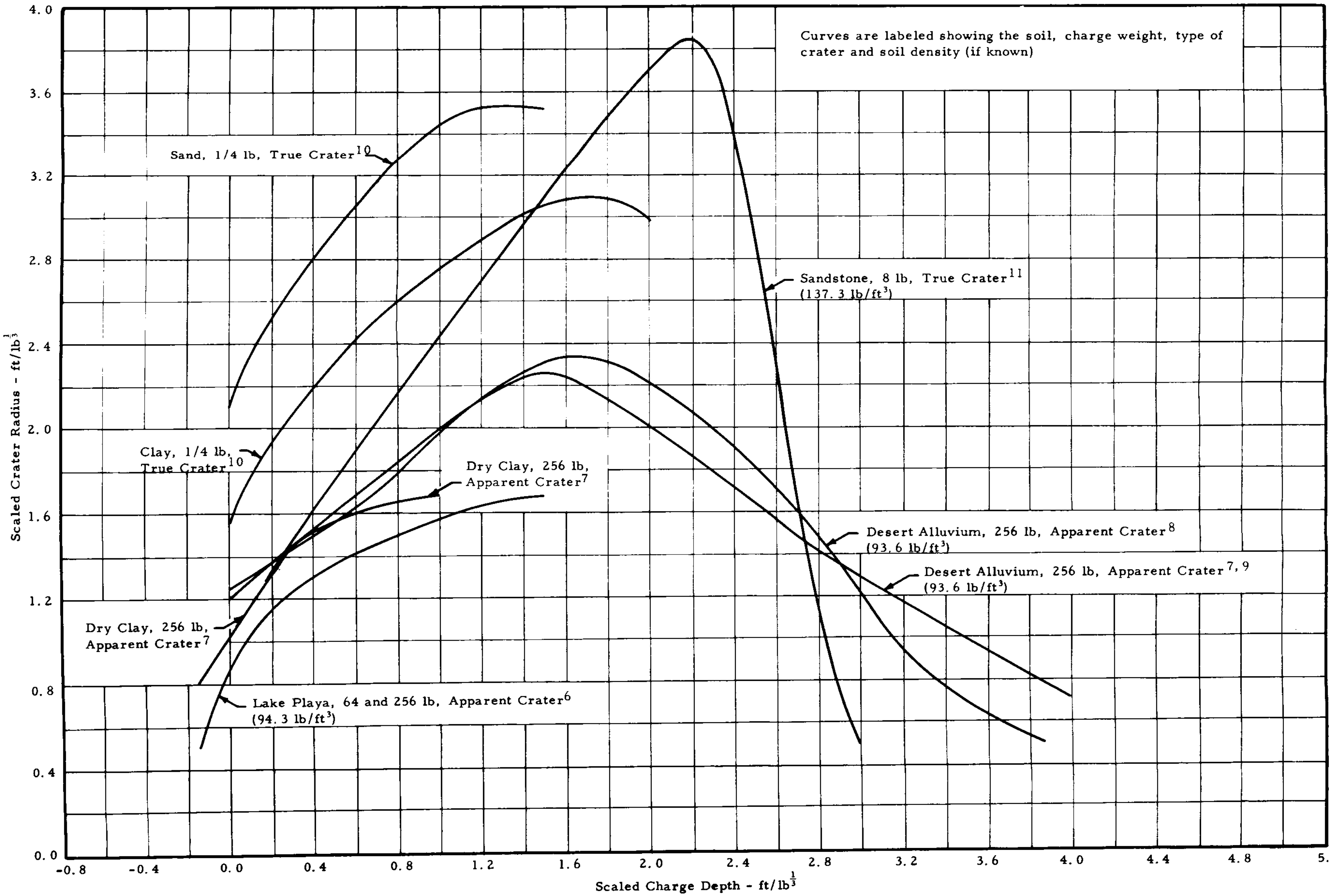


Figure 4. Scaled Crater Radius as a Function of Scaled Charge Depth for Various Soils and Charges

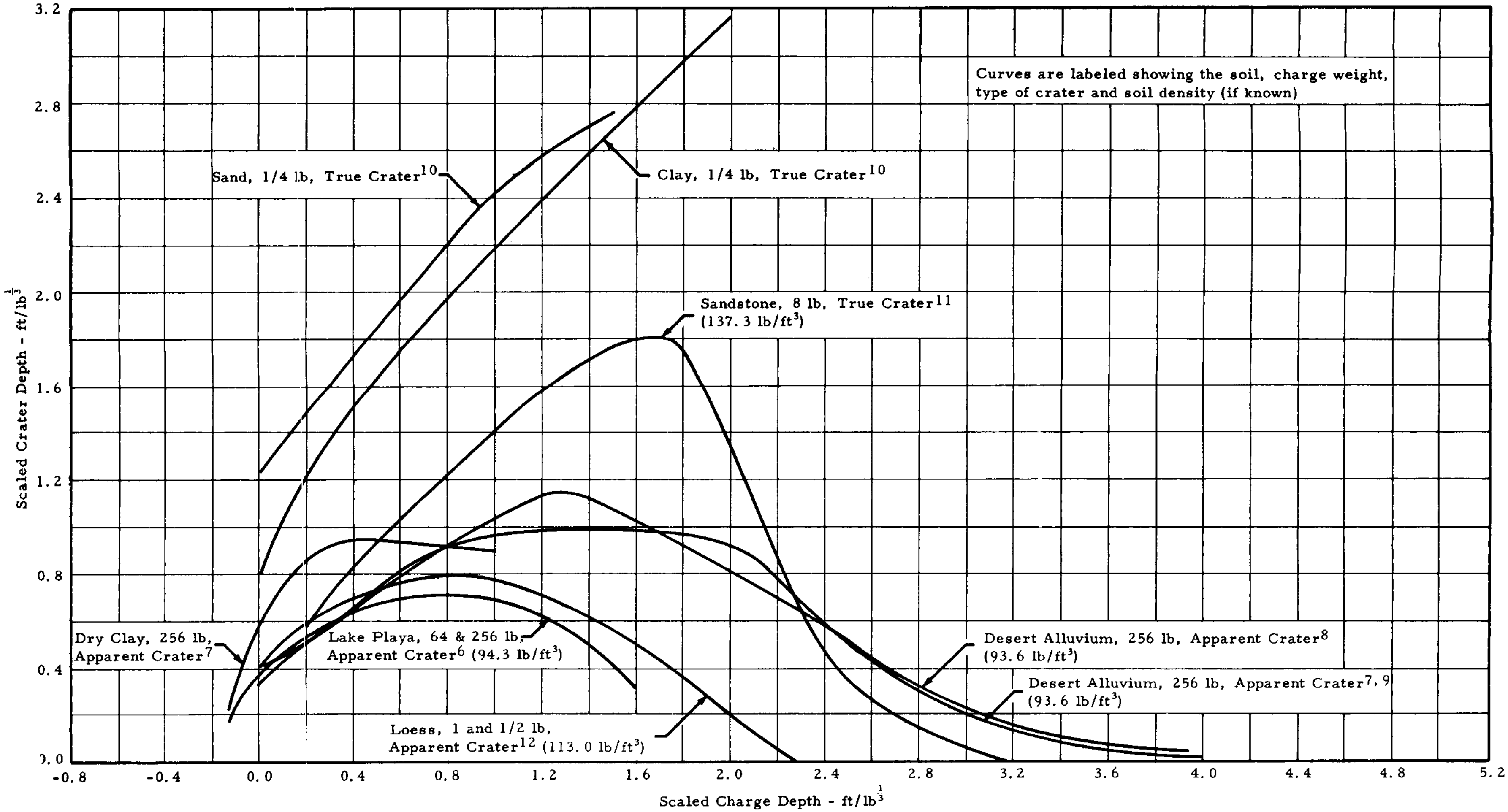


Figure 5. Scaled Crater Depth as a Function of Scaled Charge Depth for Various Soils and Charges

It then seems likely that for subsurface blasts, lunar craters will be smaller than Earth craters. Since the technique for computing volumes gives results that are slightly less than the measured volumes of Earth craters, the computed volumes would tend to be more accurate when applied to the lunar surface. The amount of ejecta is primarily a function of charge size, charge depth, and soil type. As the scaled charge depth increases, the scaled crater depth first increases and then begins to decrease. As the rock strength decreases, the crater depth increases.

Figure 6 is a plot of scaled crater volume and scaled charge burial depth for different type explosives. The soil is sandstone and the individual charge types are labeled. All weighed eight pounds. The average curve comes from Duvall's[11] values.

The variations present due to the choice of a specific kind of charge will not be considered, since the variation due to type charge is usually small compared to other variables. Values used will generally be for TNT.

A list of explosives has been compiled[13] for comparison with TNT. The value associated with the explosive is the equivalent weight of TNT that will give the same crater radius for the same charge burial depth. This is presented in Table 1.

TABLE 1

Amatol	0.94
Composition B	1.06
Dynamite (40% extra)	0.68
HBX-2	1.52
Minol	1.48
Pentolite	1.23
Tritonal	1.37

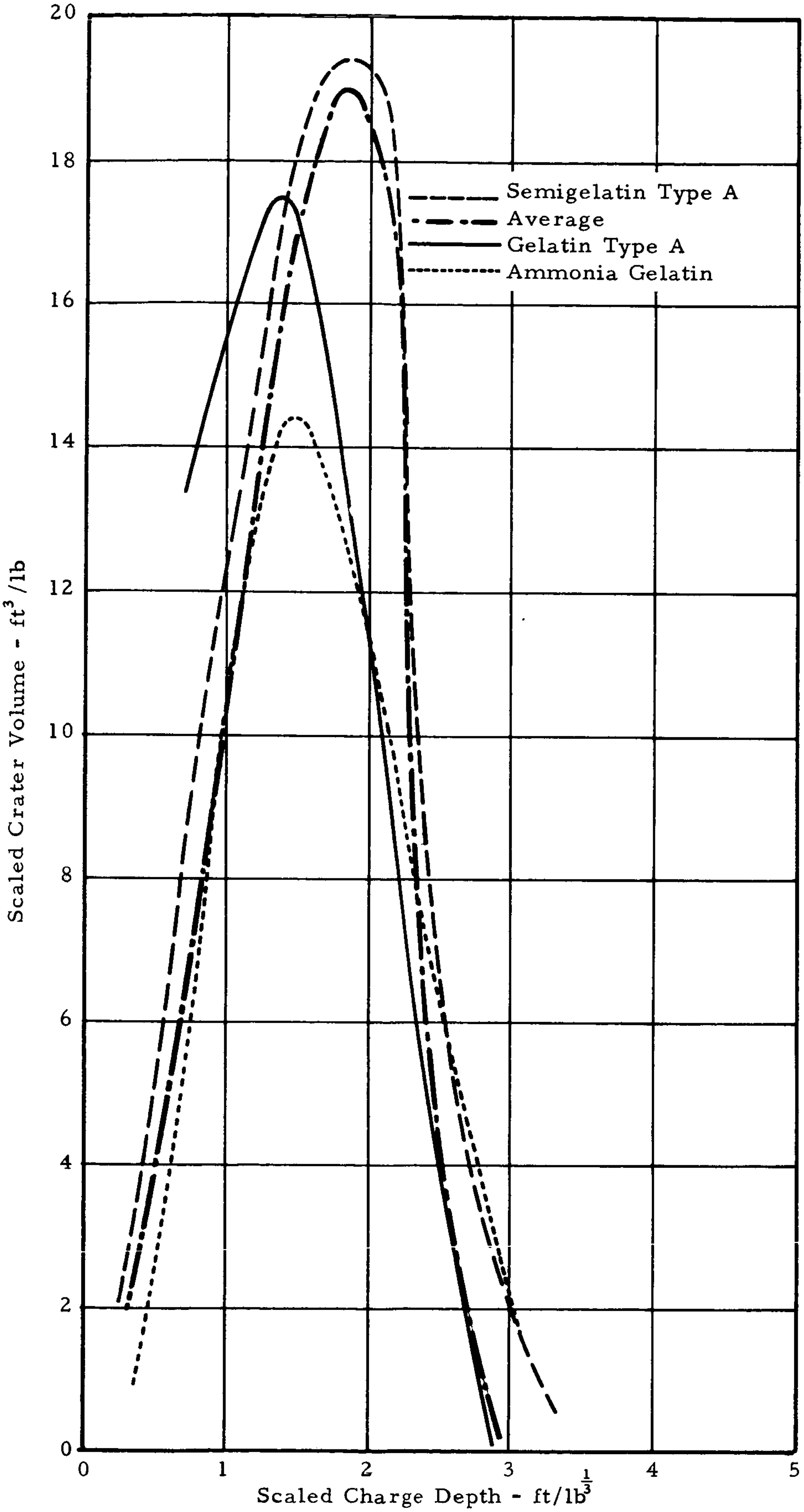


Figure 6. Scaled Crater Volume as a Function of Scaled Burial Depth in Sandstone

It seems reasonable to say that gravity will be an influence in the crater's size. It seems doubtful that the true crater dimensions will be affected, but less fallback should be present in a weaker field. This should lead to more mass around the crater's rim but should not affect the amount of mass under consideration in this report.

The soil that is situated below the charge is compressed, and the soil to the side of the charge is scoured out. When charges are buried within one-half scaled foot of the surface, the true crater is composed primarily of scoured material and is saucer-like in shape.

When a charge is placed at or above surface level, most of the broken and displaced surface material does not fly away from the crater. Above-surface blasts in the lunar vacuum will not have an atmosphere to propagate a shock wave to the soil. Except for a small fraction of the blast strength reaching the surface by way of the expanding gases of the explosion and shattered pieces of the charge casing, nothing should cause a disturbance of the soil. Unfortunately, the coupling of charge energy to the soil will be too poor for seismic testing.

For surface detonations, the variation of the crater size as the weight of the charge changes is small but compaction of the soil is greatest. The ejecta is only about 60 percent of the apparent crater[6], and the crater itself is small. If technology allows it, the charge should be buried deep enough so that no ejecta appears. To minimize danger due to ejecta, charges should be placed at surface level or slightly below it (just deep enough for adequate coupling and yet shallow enough that the amount of ejecta is small). If the nature of the lunar surface layer makes it necessary to bury a charge deeper in order to get an adequate wave propagated, the charge should be buried below the level which gives the maximum amount of emitted mass. The danger at some ground ranges actually increases for a while as the charge is buried deeper.

Once the total mass of ejecta is known, particle size distribution must be considered. Rogers[14] presents numerical data for maximum block size of debris from a ballistic crater. Figure 7 presents the same data plotted on a different set of scales. The data comes from measured debris of craters formed by hypervelocity impact. Current thought on the mechanism of hypervelocity impact indicates that this method of crater formation is similar to that of high explosion (if not actually a high explosion itself), and the craters that come from both sources are frequently identical. The major problem in this area is to determine the relationship between chemical explosive and particle size momentum. However, all that is necessary here is a relation between crater size and maximum block size.

Tests in pumice indicate that for small mass hypervelocity impact, most ejecta mass is concentrated in intermediate sizes. Solid rock and particulate material have heavier mass concentration at sizes approximating the largest size[15]. In any event, clay minerals (smaller than 0.002 mm) will not generally be produced by an explosion[16]. Earth tests show that fragmentation patterns are influenced by pre-existing lines of weakness while spray patterns are roughly symmetrical about a center.

The Earth's atmosphere acts as a sorting agent. Different size particles experience different air resistance, and since the particles are lubricated by the atmosphere they tend to separate. These effects are not present on the Moon. Lunar particles, being uncontaminated, will possess grain-to-grain friction coefficients of from 5 to 50 times that on Earth. The actual size of the particles will be based almost entirely on the size of the particles found on the Moon's surface and the strength of the band that holds them. Based on hypervelocity impact studies[15], it seems unlikely that many existing grains will be fractured or crushed. It can be assumed that the ballistic particles will be larger at the impact point than is experienced here. This fact seems likely to induce increased size among the smaller particles rather than among the larger ones.

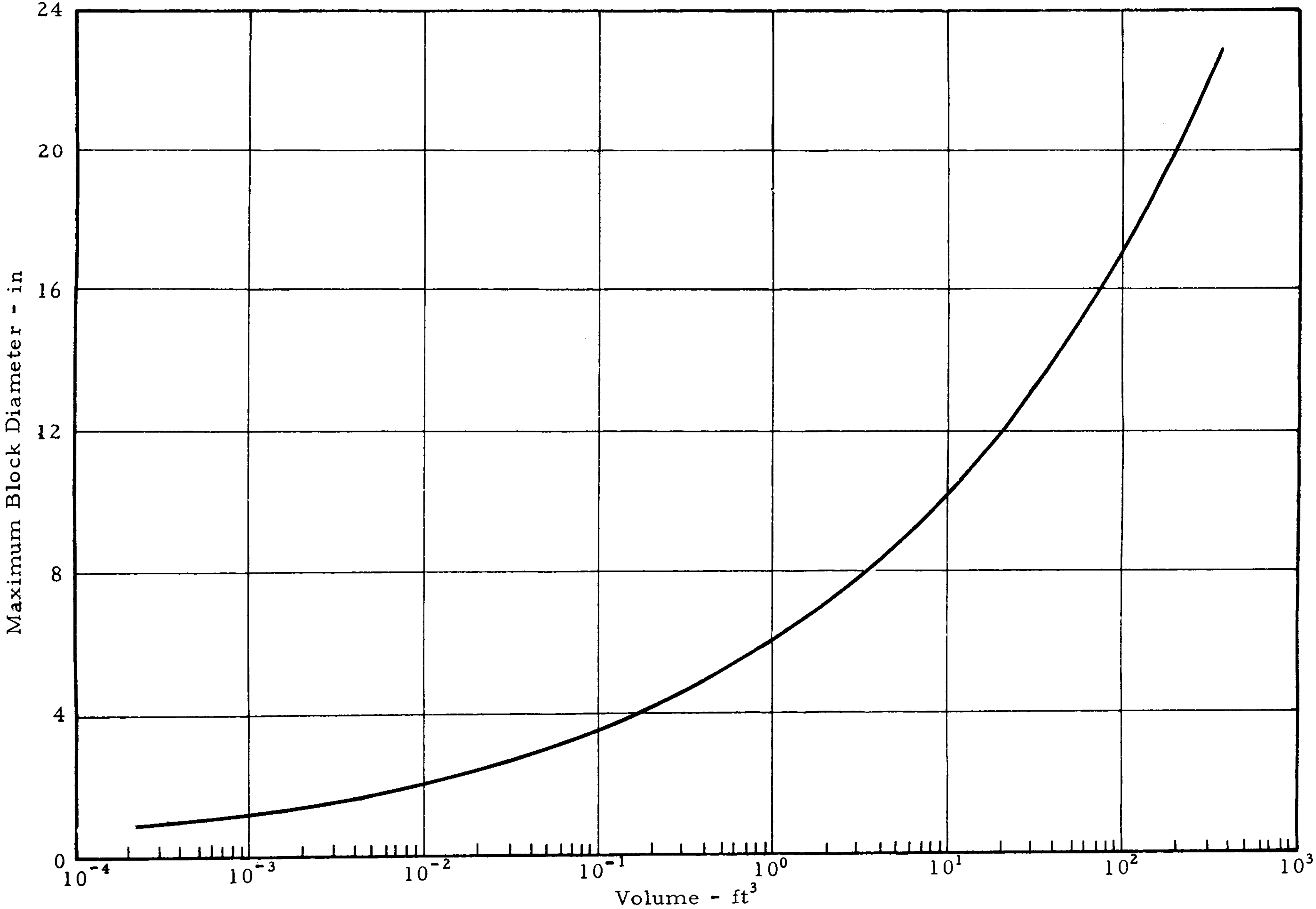


Figure 7. Maximum Ejecta Block Diameter as a Function of Impact Crater Volume

INITIAL VELOCITY OF EJECTA

In order to determine what the areal density of crater ejecta material is at any ground range, the velocity and ejection angle for all initial positions of the ejecta must be known. Motion picture films of explosions have been helpful in determining maximum initial velocity of surface particles, but it is impossible to use this technique to study how velocity varies from point to point along the surface, or to determine the velocity of the subsurface particles. Scattered dust and combustion products often make it impossible to get visual observations.

In a few experiments, soil was stained or markers were buried before the explosive was detonated. By examining post-shot positions, and taking atmospheric effects into account, estimates of initial velocities can be obtained. There are, however, only a few reports available which have done this, and unfortunately the results are not consistent enough to be used with confidence. Even if initial and final positions are exactly known and the influence of the atmosphere can be taken into account, there are still two unknowns: the speed and the direction at each initial position. Both cannot be solved by simply knowing the two rest positions.

To solve for the speed, an initial angle must be assumed. All particles within a conical shell have the same ejection angle, namely that between the horizontal and the line that connects the particle with the apex of the cone. The location of the apex of the cone is still undetermined. One convenient and reasonable position for this apex would be at the center of the explosion. This theory is subscribed to by a number of authors[6, 17, 18, 19]. Another view advanced is that particles diverge from an "epicenter" not coincident with the charge[18, 20]. The epicenter is on the vertical line that passes through the charge, but its depth varies. Ahlers[20] claims that each depth level has an epicenter. He gives an equation for the velocity at any point

$$v = k \rho^{-m}$$

where

$$\rho^2 = r_i^2 + \tau^2 (X_e - D_p)^2$$

r_i - initial ground range,

X_e - epicenter depth,

D_p - depth of particle, and

k, τ, m - constants.

The ejection angles are considerably flatter and ejecta spray closer to the crater if particles diverge from an epicenter rather than from the buried charge. The largest variation would take place with the greatest ejection angles, but fortunately this includes only the smallest fraction of the total ejecta. Actually, there are no claims of being able to state the direction of this portion of the crater. The speed is greatest, but the direction is unpredictable.

This report will assume that all particles included in Section I of Figure 8 diverge from the charge center. Particles in Section II are ejected from the crater but at a low velocity. This is due to either a large initial distance from the explosion or a loss of most of the original energy due to collisions before reaching the surface. This section accounts for almost all of the nearby crater rim. Section III consists of crushed rock and fallback material. Only Section I will be considered when discussing the hazard at any reasonable distance from the explosion.

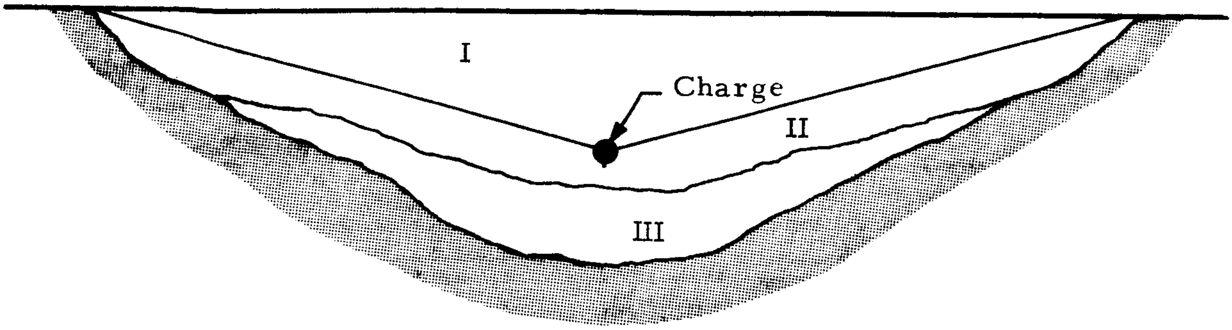


Figure 8. Crater Profile when Charge Depth is Less than Crater Depth

The volume ejected between angles θ_i and θ_f is

$$\frac{\pi}{3} D_C^3 (\cot^2 \theta_f - \cot^2 \theta_i)$$

where θ is the elevation angle and D_C is the charge depth.

If the charge depth is greater than the crater depth, the ejecta still radiates from the charge, but the volume for each ejection angle extends from the surface to the bottom face of the hollow. Most of this volume is shaded in Figure 9.

The volume ejected between angles θ_i and θ_f is

$$\frac{\pi}{3} (\cot^2 \theta_f - \cot^2 \theta_i) D \frac{(R \tan \theta_i - D_C)}{(R \tan \theta_i - D)} \left[3 D_C{}^2 - 3 D_C D \frac{(R \tan \theta_i - D_C)}{(R \tan \theta_i - D)} + \frac{D^2 (R \tan \theta_i - D_C)^2}{(R \tan \theta_i - D)^2} \right] .$$

This is derived in Appendix A.

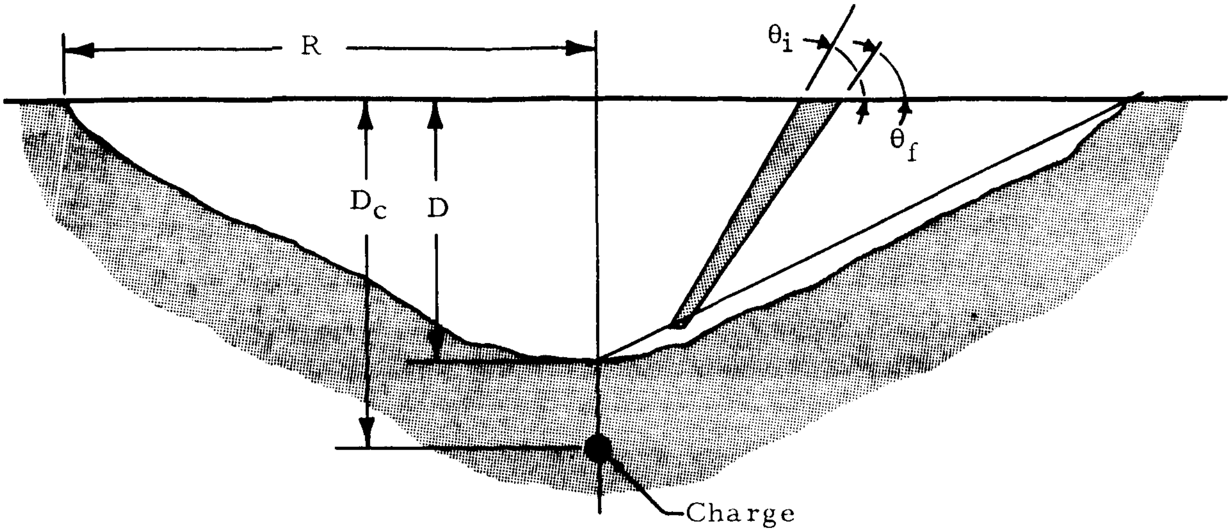


Figure 9. Crater Profile when Charge Depth is Greater than Crater Depth

Ahlers[20] presents data for the magnitude of the velocity at various positions in the crater. Figure 10 is a plot of lines where the magnitude of velocity is constant. Although the charge used was 20 tons of TNT, a weight much greater than this report utilizes, it perhaps indicates that these constant property lines are roughly radial about the charge. Unfortunately, similar data could not be obtained for small, high-energy explosions.

Vaile[19] found that

$$v = \frac{A}{\lambda^n} (\sin \theta)^n \tag{1}$$

where

v - exit velocity at the surface,

A - constant,

θ - ejection angle

λ - scaled charge depth, and

n $\approx$ 1 or 2.

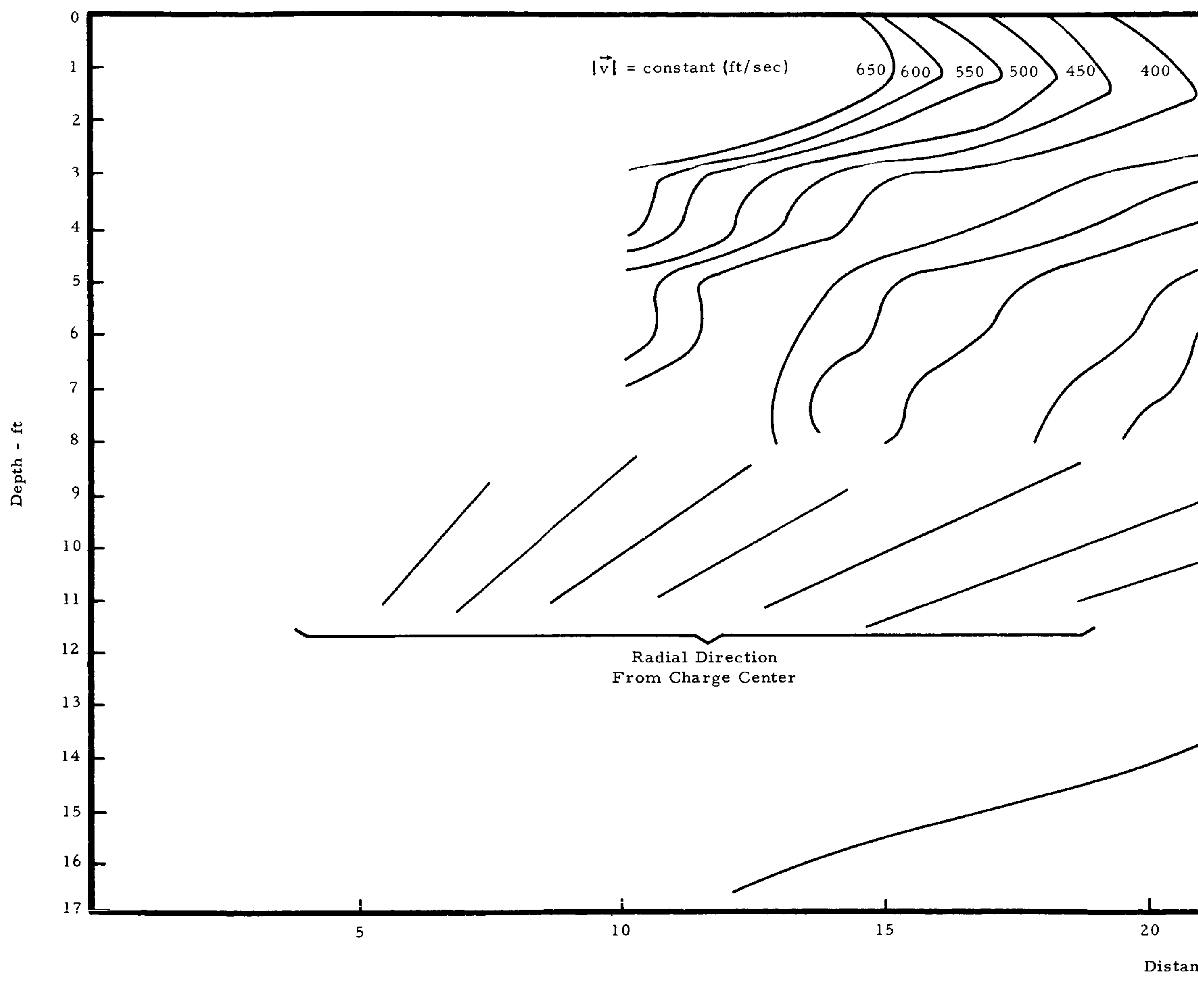
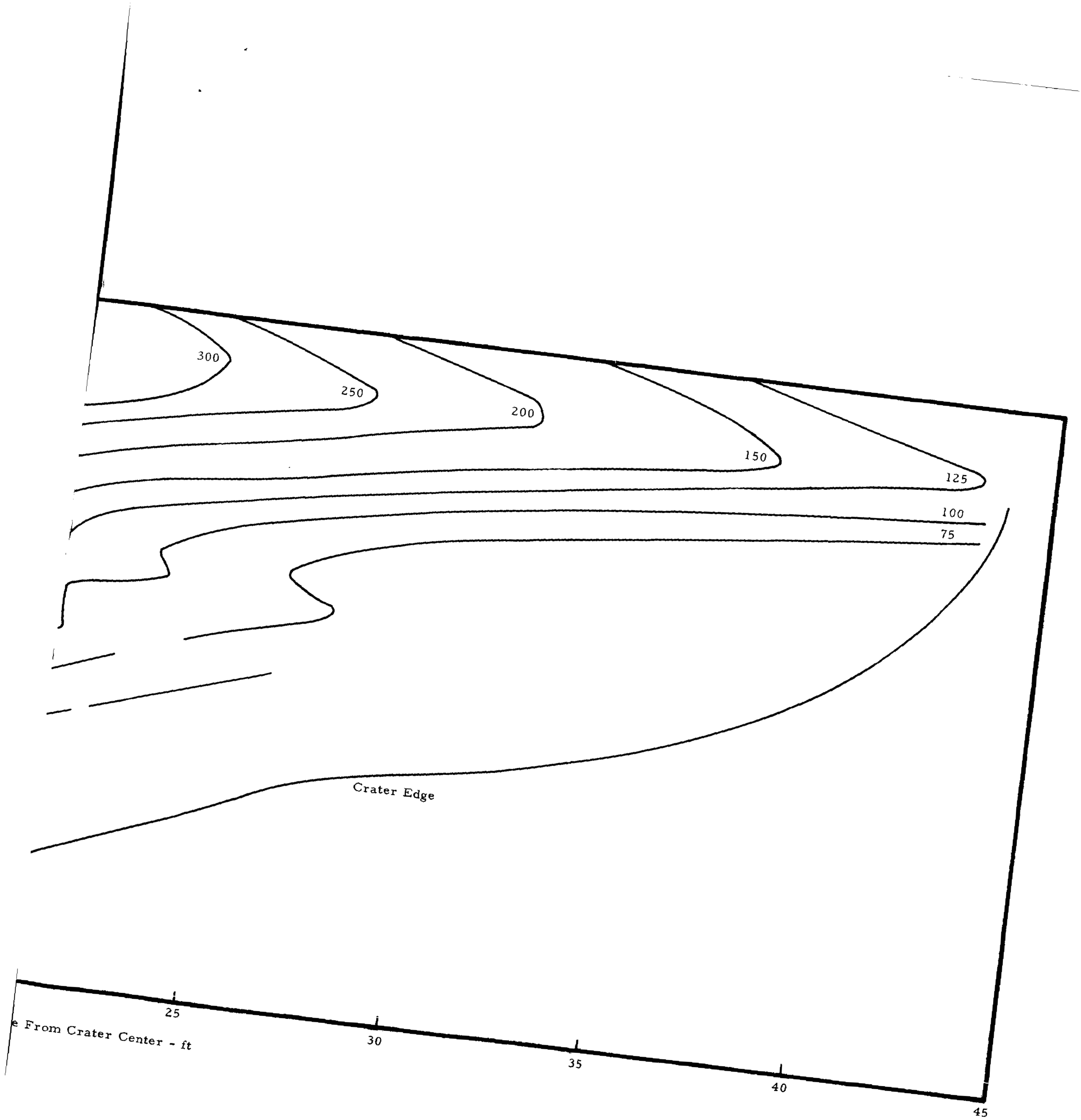


Figure 10. Line Profiles of Velocity Magnitudes for 20-Ton Charge of TNT in Alluvium

21


300
250
200
150
125
100
75
Crater Edge
25
30
35
40
45
e From Crater Center - ft

Since at $\theta = 90°$ v is equal v_{max}, A must be equal to $v_{max}\ \lambda^n$. Values for n can be found using the data from Figure 10. The averaged value of n was 2.71 but it showed no recognizable dependence on θ, although θ ranged from 20° to 60°. The value of n is mostly dependent on the soil and nature of the explosive.

Murphey[8] states that in desert alluvium the maximum velocity at the surface decreases about as the depth of blast to the 2.2 power. If it is assumed that the velocity of any point on the surface is dependent upon the distance to the charge to the -2.2 power, then

$$v \approx \frac{1}{d^{2.2}} = \frac{\sin^{2.2}\theta}{D_C^{2.2}} \approx \frac{\sin^{2.2}\theta}{\lambda^{2.2}} .$$

This form agrees with Equation 1 if n is equal to 2.2.

Similar results of tests are presented[18] where

$$v_{max} = A\lambda^{-n}$$

and

$$v = v_{max}\sin^3\theta = \frac{A\sin^3\theta}{\lambda^n}$$

for $33° > \theta$. The value of n depends on the soil and takes on some values as listed in Table 2. The form of this equation also resembles Equation 1, although here the exponents of λ and $\sin\theta$ are not always equal to each other or to 2.2.

TABLE 2

Soil	Rock	Clay	Sand	Loess
n	1.5	1.8	2.4	3.0

Some measurements have been taken for the maximum velocity of the surface particles after an explosion in sandstone[11] and desert alluvium[8]. Curves based on the values attained are plotted in Figure 11. Charge size ranged from 0.4 to 256 pounds. Using scaled charge depth as one of the variables gives results that show fairly good consistency. Values taken from experiments performed by the U. S. Army Ordnance Ballistic Research Laboratory, Aberdeen Proving Ground, show good correlation with the results. The curve

$$v_{max} = \frac{A}{\lambda^{2.2}}$$

matches the plotted curves quite well when A is equal to 95. The tests at the Aberdeen Proving Ground also showed that the energy transmitted to the ground by a surface explosion was the same in vacuum as in an atmosphere[21].

Based on this discussion, the relationship that will be used in this report to find the velocity at any point in the crater is

$$v = \frac{A}{\lambda^n} (\sin \theta)^n \tag{2}$$

where $n = 2.2$ and $A = 95$. The computer program accepts n and A as parameters so that it will be possible to maintain the program's effectiveness if future knowledge of the lunar surface provides better values.

Equation 2 breaks down as $\lambda \to 0$. Physically there are reasons why this model should not remain valid. The geometry and finite size of the explosive becomes a dominating feature that must be accounted for when predictions are attempted.

The situations depicted in Figure 12 have radically different ejecta patterns although the weights and scaled depths are the same for each case. The amount of soil immediately above the charge can vary,

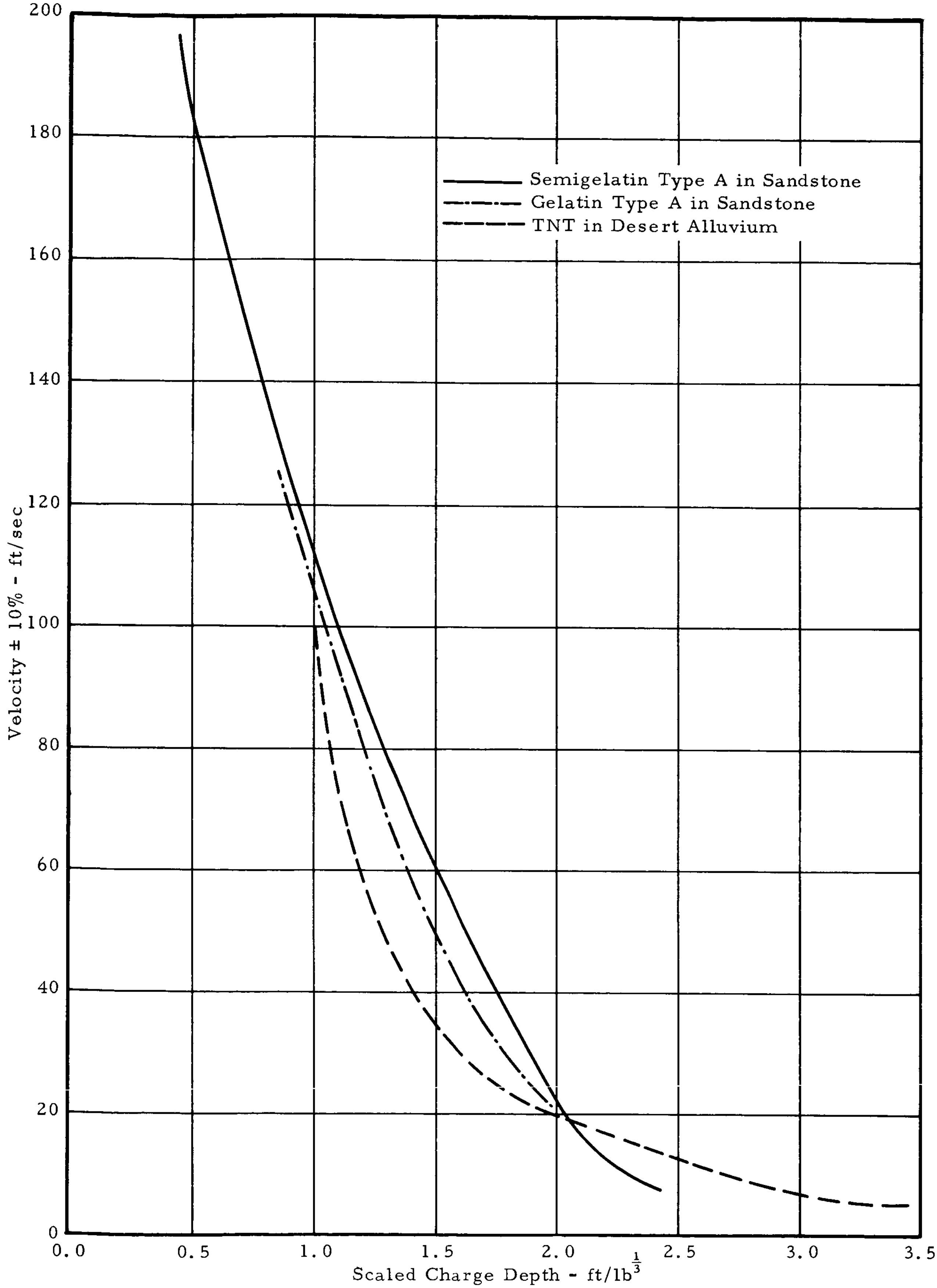


Figure 11. Surface Fly-Rock Velocity as a Function of Scaled Charge Depth for Various Explosives and Soils

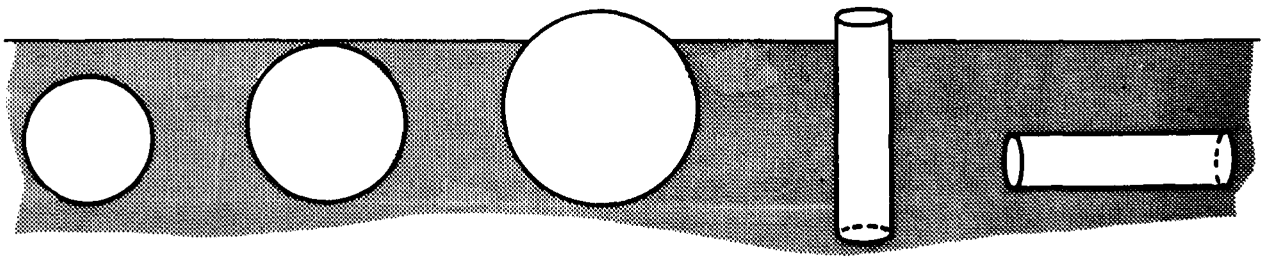


Figure 12. Possible Charge Shapes and Positioning

and in fact there might not be any soil at all. The velocity distribution will not be identical in any two situations. In addition, as the charge is placed very close to the surface the assumption that Section I of Figure 8 is the only one from which matter is thrown ballistically becomes increasingly in error. Section II will have particles that rebound and still have an appreciable velocity as they leave the crater area. Section II will also have significantly more mass to contribute than Section I, none of which the model can take into account.

Near surface detonations produce a crater that is saucer shaped. Most of the mass was originally at the side of the explosive and is ejected at low angles. This means that the amount of mass whose velocity is in doubt, namely that directly or almost directly above the explosive, accounts for only a small fraction of the ejecta. Therefore, results of the discussed model have some meaning as long as λ is greater than zero. To predict how much mass Section II contributes is impossible at this time. It will be highly dependent on the soil's strength. Whenever the depth of the charge is comparable to the size of the charge, mass calculations as a function of ground range should be viewed as underestimations of the actual case.

In order to use Equation 2, an upper limit for the velocity must be set. Even with the charge placed near the surface only a small portion of the total ejecta can experience this upper limit. The limit will be 6500 ft/sec and is based on some maximum velocities that have been attained by shrapnel of military explosives. It can be pointed out that the velocity of escape is ~7800 ft/sec and that for circular orbit is ~5540 ft/sec at a 0° ejection angle[5]. Neither condition will be met.

Another possible source of error in Equation 2 is the assumption that all particles with the same ejection angle have the same velocity. This has been previously discussed, but it can be easily shown that half the mass of each conical shell is located within only one-fifth of the charge depth from the surface. Even if the velocity of the deeper particles were to differ from that of those near the surface, the percentage of mass affected minimizes the importance of this assumption. Indeed, the mass located within the lowest fifth of the conical shell (near the apex) is only 0.8% of the mass of the entire shell.

BALLISTIC EQUATION

In view of the initial velocities involved and the uncertainties encountered, it is not necessary to deal with central force field equations.

The ballistic range (R_b) is then given by

$$R_b = \frac{v^2}{g} \sin 2\theta$$

where

v - magnitude of velocity and is given by Equation 2,

θ - ejection angle with the horizontal, and

g - acceleration due to lunar gravity.

Using Equation 2 the ground range from the center of the crater is

$$R_g = \frac{2A^2}{g\lambda^{2n}} \sin^{2n+1}\theta \cos\theta + D_c \cot\theta \quad .$$

AREAL DENSITY

The computer program accompanying this report computes the mass per unit area for all ground ranges. Symmetry about the center of the crater will be assumed. In actuality this is never the case. Rays of ejecta occur because discrete masses of unconsolidated material can be ejected as a unit. If the ground is not homogeneous, it will be broken up irregularly by the shock wave. Pre-existing fault lines can also cause an asymmetric condition. The smaller the charge, the more important this condition becomes when accurate results are sought. Unfortunately, little can be done about this problem other than acknowledging its existence.

Each ground range, except at the maximum, has a contribution from both high and low angle ejecta. The initial speed decreases as the ejection angle decreases (see Equation 2), but the mass associated with lower ejection angles is usually greater than for higher angles. Therefore, each ground range usually has a contribution of high velocity, high impact angle and a lower velocity, lower impact angle, with the greater percentage of the mass being concentrated in the latter case.

At ground range of a few crater radii most of the mass is a result of scoured ejecta and upthrust of the soil adjacent to the crater. This will not be accounted for in this report so results for mass deposits within a few crater radii will not approach the actual case.

The greatest areal densities occur when the charges are buried deep. This, however, gives low velocities.

The curves presented in Figures 13 through 17 are based on the output of the computer program. All are based on an assumed soil density of 50 lbm/ft^2 and values of 2.2 and 95 for n and A respectively. It should be noted that the curves do not and should not represent typical crater lip profiles. Only Section I of either Figure 8 or 9 is represented. It is only at distances greater than about 8 crater radii that the curves developed will fit the actual depris curve. For small charges the thickest section of depris is only about 0.006 inch deep. This applies to all five typical cases represented in Figures 13 through 17. Many of the values for the mass per unit area are so small that the corresponding heights would be of the order of an atomic radius or less. The model assumes a uniform spread over the ground.

In any actual case the smallest particles determine the limit of how smooth the distribution can be. It is unlikely that any particles will be finer than about 8×10^{-6} ft (Reference 16). For a density of 50 lbm/ft^3 and a spread of particles one deep, the mass per unit area could then have a minimum value of 4×10^{-4} lbm/ft^2. Any number that approaches this value or is lower should be viewed in terms of the probability that ejecta will land at that given range. In connection with this, it can be seen that Figures 13, 15, and 17 show a sharp peak in the curve as the range approaches its maximum value. The reason that it is often more probable to expect ejecta to land at the maximum rather than at some lesser range is that as the ejection angle approaches the angle that will give the maximum range, an increment in the angle produces a rather small range increment. A conical shell with ejection angles between 65° and 66° might be spread over a ground range of 2 feet while a shell of particles ejecting out from 40° to 41° may fall over a 30-foot range.

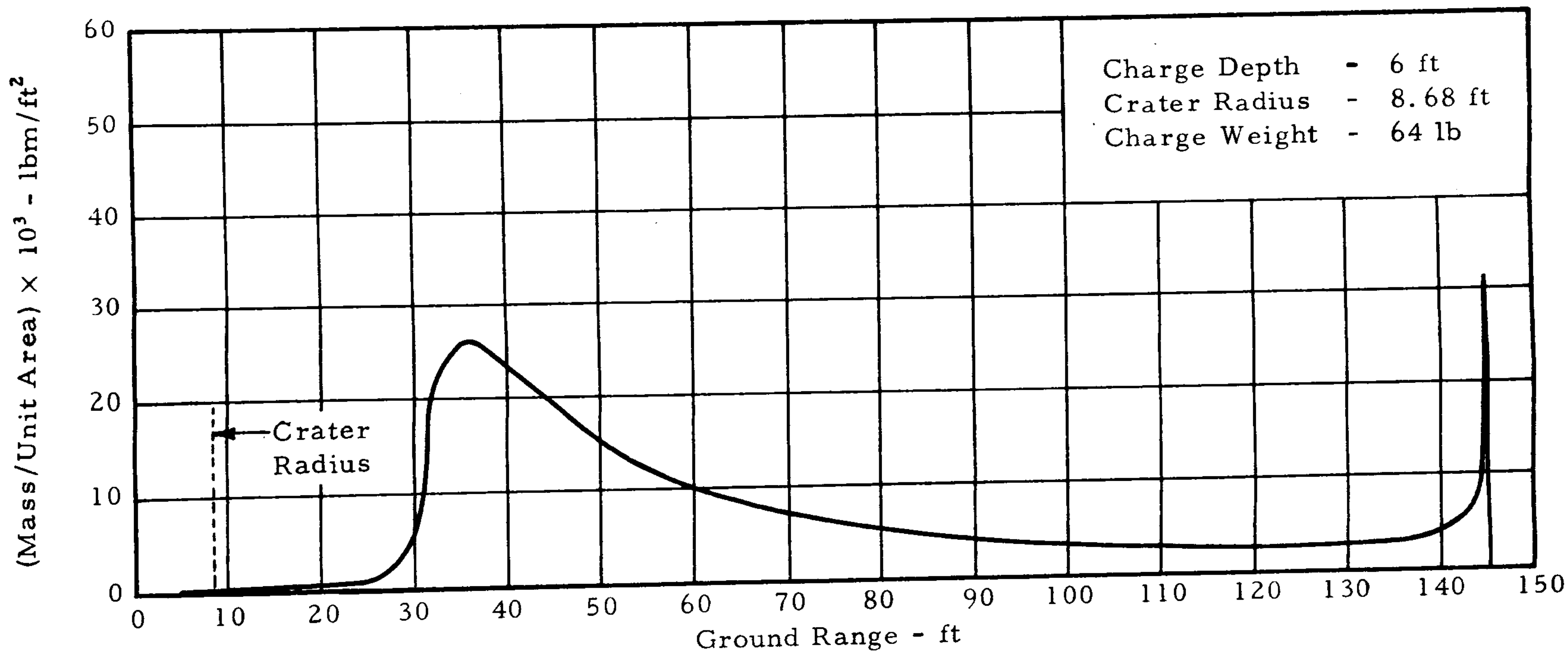


Figure 13. Mass per Unit Area as a Function of Ground Range from the Crater's Center

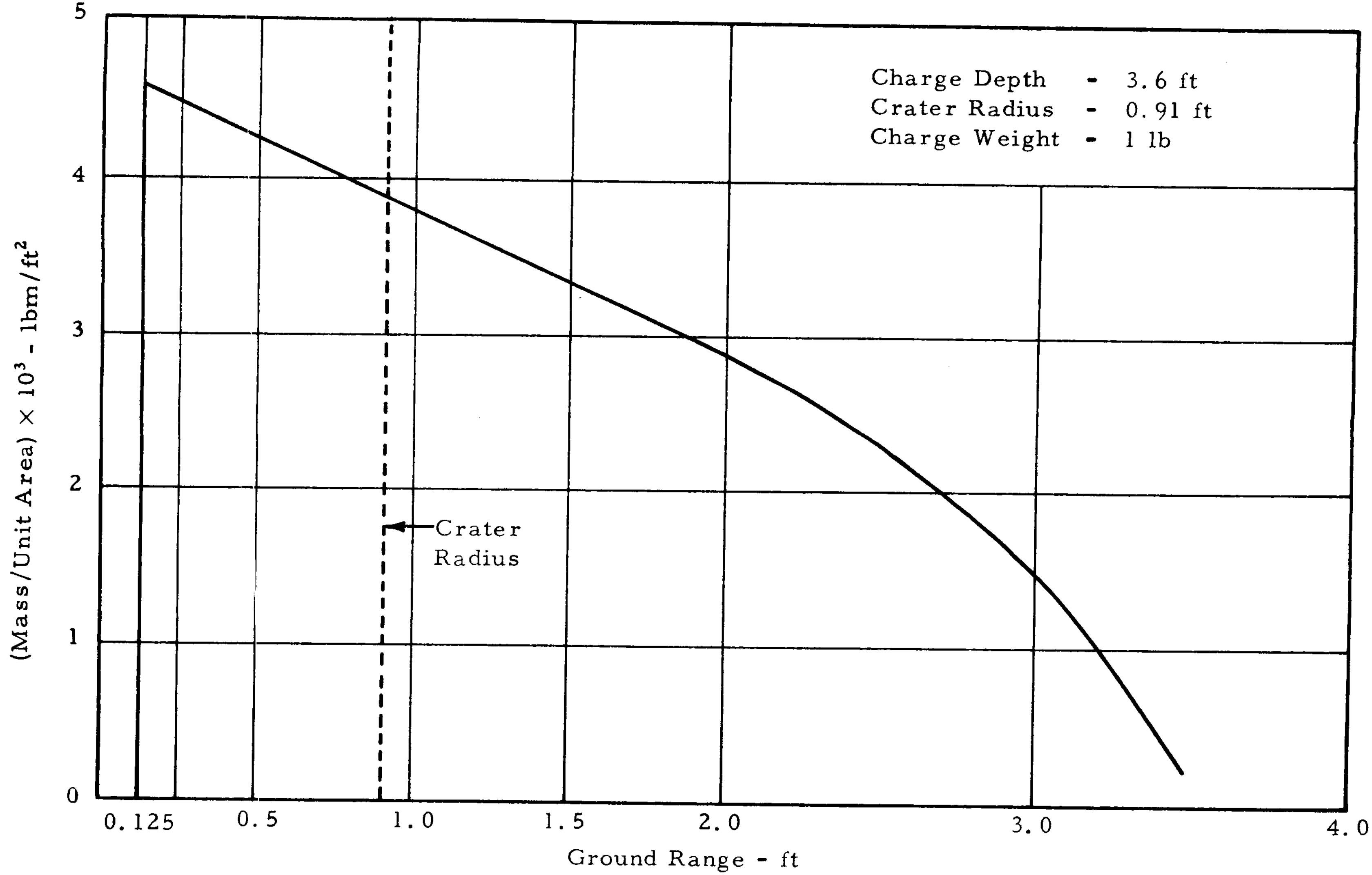


Figure 14. Mass per Unit Area as a Function of Ground Range from the Crater's Center

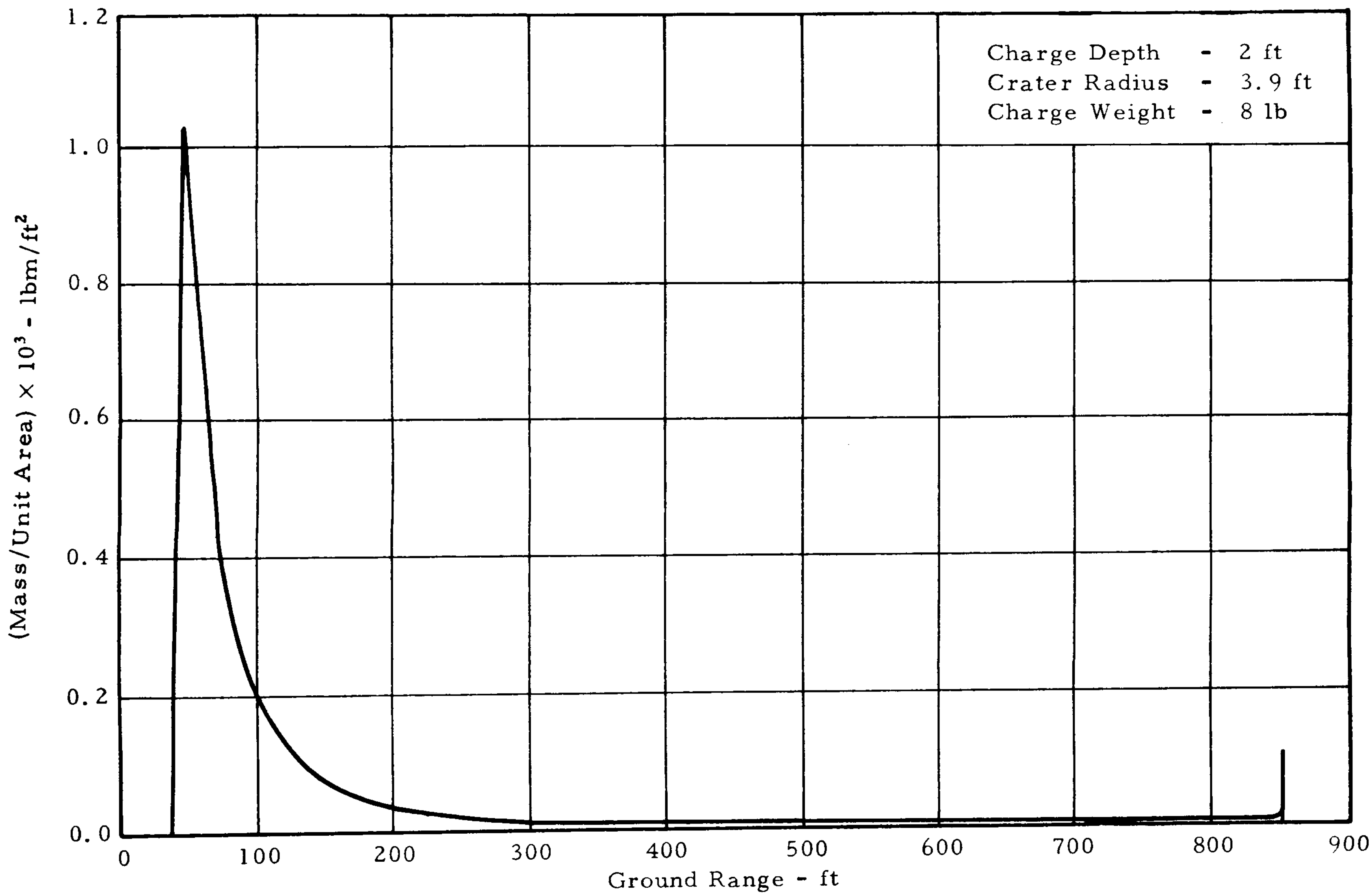


Figure 15. Mass per Unit Area as a Function of Ground Range from the Crater's Center

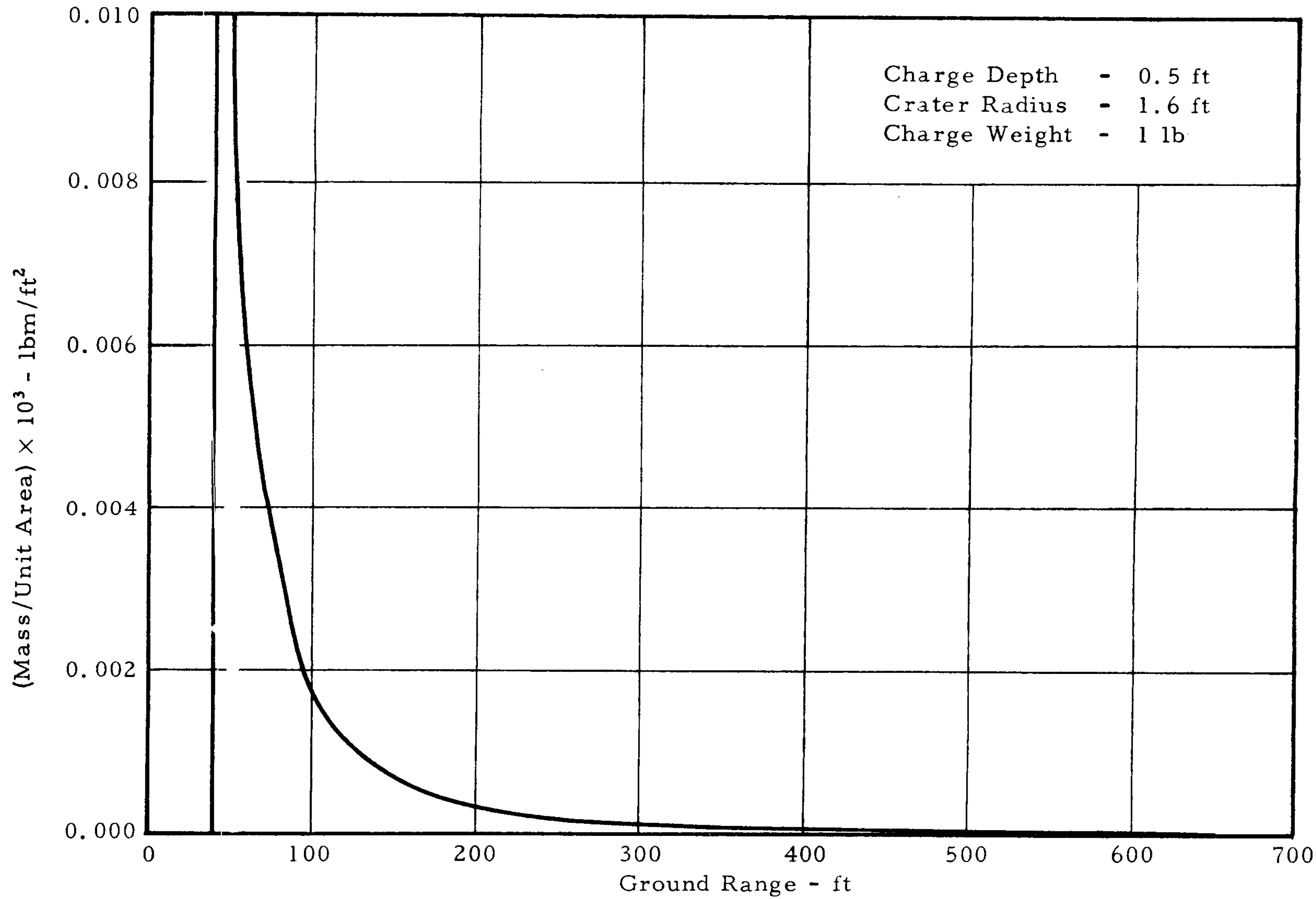


Figure 16. Mass per Unit Area as a Function of Ground Range from the Crater's Center

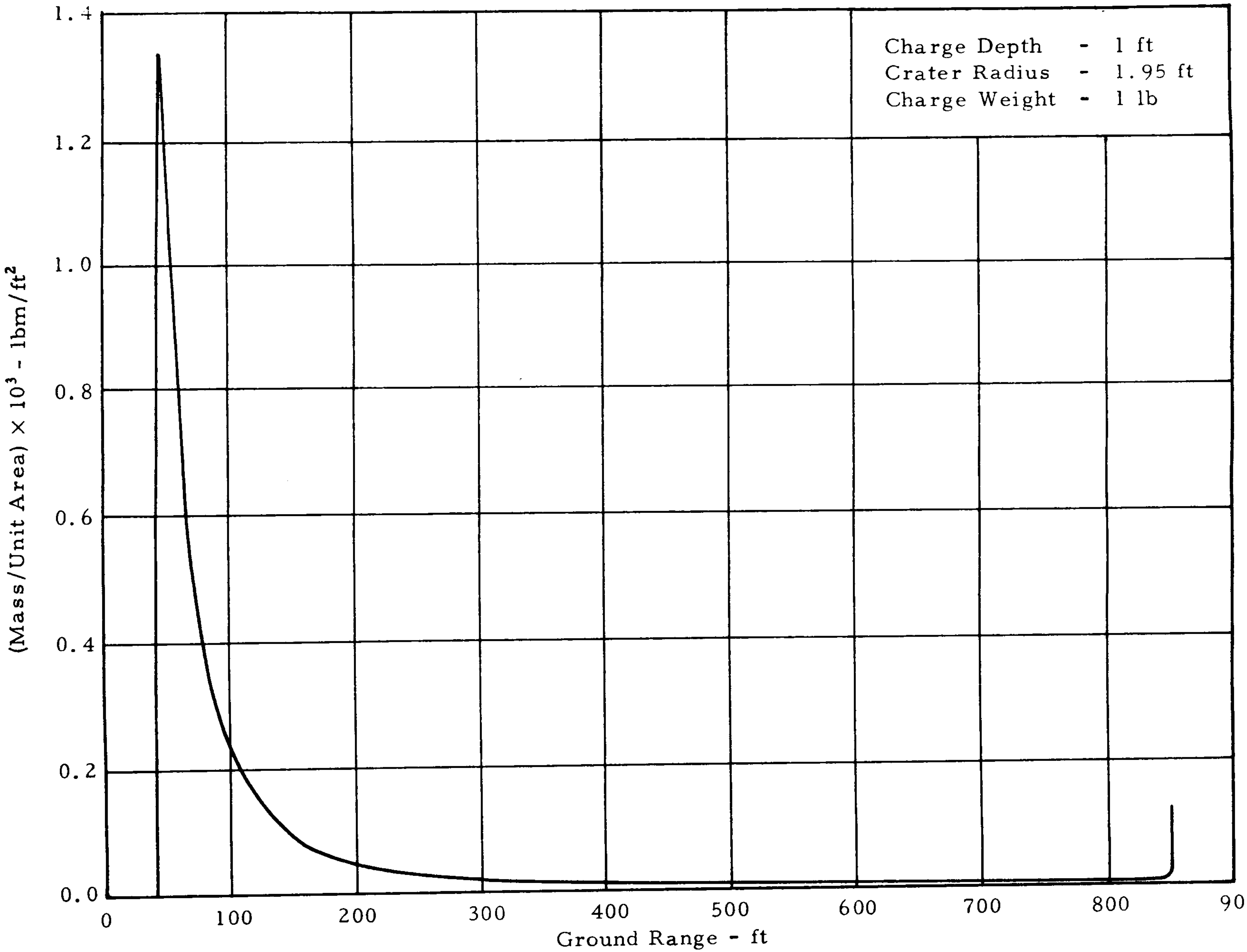


Figure 17. Mass per Unit Area as a Function of Ground Range from the Crater's Center

SECONDARY EJECTA

In the discussion of debris, consideration must be given to the possibility of some debris occurring that does not originate in the crater. It is the result of the impacting of ejecta upon the soil. Lunar features indicate that secondary cratering occurred in many instances. Of course, neither the masses or velocities that caused these known events is similar, within order of magnitude, to what is presently under consideration. This implies that the visual observation of secondary craters on the Moon should not induce one to decide that they will be a problem when dealing with small explosions.

It is possible to have a particle impinge on a surface and expel a total mass greater than itself. Some particles can also be ejected at a higher velocity than that of the impacting particle. These facts are common knowledge in hypervelocity impact studies. Naturally the laws of conservation of energy and momentum need not be, and of course are not violated. However, since hypervelocity is beyond the range of velocities under consideration, there should not be any predisposition for believing that secondary ejecta will be a problem.

Even experience with loose vesicular soil and light, low velocity projectiles is invalid because of the influence of the Earth's atmosphere. The atmosphere acts as a lubricating medium. Although individual experiments often show great variation, the trend is for less penetration as atmospheric pressure decreases[22]. The best vacuums attained in these tests have been approximately 10^{-8} to 10^{-10} torr as compared to a lunar vacuum of 10^{-14} torr.

With typical velocities of 10-400 ft/sec and particle sizes that may be as large as one foot in diameter, it is impossible to predict the seriousness of secondary ejecta. McCracken and Dubin[23] suggest all momentum might be absorbed in an inelastic medium. On the other hand, it is possible to imagine the total weight of particles landing at any given range to consist almost entirely of secondary ejecta. The model will make no assumptions on this matter. The problem will be treated without the possibility of secondary ejecta occurring, and all answers should be judged in that light. It would seem unlikely that multiplication by more than a factor of two would be necessary for correction.

THE MAIN PROGRAM

The user of the program will be able to supply the following parameters:

1) The weight of the charge in pounds of TNT.

2) The scaled depth at which the center of mass of the explosive will be buried. It should be greater than zero as outlined in the discussion that follows Equation 2.

3) The depth and radius of the crater which will result. These values are to be obtained from Figure 2 and are to be given in the scaled values presented.

4) The value of n, the exponent in the equation

$$v = \frac{A}{\lambda^n} (\sin \theta)^n \quad .$$

This value depends on the lunar soil properties. It should be 2.2 until future knowledge of the surface material indicates that a different value should be used.

5) A is the constant which gives the best fit of the equation

$$v_{max} = A \lambda^{-n}$$

to the velocity curve in Figure 11. When n = 2.2, A is 95.

6) ρ, the density of the lunar surface material. This is unknown at the present time, but the surface layer should have a value of from 37.5 to 93.6 lbm/ft^3 (Reference 24).

7) Maximum range increment. The ejection angle is monotonically decreased by an assigned decrement. The conical shell of material ejected within each angular range is spread over a ground range. If this ground spread is greater than the maximum ground range increment desired, the angle decrement is decreased. This quantity need not be specified, in which case it will be set equal to one-tenth of the maximum range.

The output of the program is a listing of ground ranges and the mass and velocities associated with them. A sample run is presented in Appendix B.

SUMMARY AND RECOMMENDATIONS

The surface being considered will be a loosely packed, lightly cemented mixture of small particles, such as desert alluvium. Explosive size should be confined to under ten pounds, but scaled data of larger explosions will be used to get empirical values of crater dimensions.

The volume of ejecta to be considered is conical in shape. The volume equations differ depending on relative depths of the crater and explosive. The initial velocity of any point in the crater is given by

$$v = \frac{95}{\lambda^{2.2}} (\sin \theta)^{2.2}$$

and its range is derived from vertical rather than central force field considerations. The mass landing within any range is found so that the components that make up the total momentum at any range are known.

When specific answers to questions about inaccessible objects are sought, a good deal of educated guesswork is necessary. Materials with some similar properties can be used to predict other properties. Just how close the results are to the real situation is always debatable. It becomes advisable then to vary a number of situations to see how seriously various answers become affected as some of the unknowns change.

There are a number of experiments that can be carried out before landing on the Moon that should help in judging how close empirical data for Earth explosions fits the situation on the Moon.

Small charges can be detonated in soils with different cohesive properties. Volcanic ash should be included. It is important to keep an extremely high vacuum and low moisture level. By means of films and premarked soil, velocity determinations including ejection angles should be studied. This applies to subsurface as well as surface particles.

The questions concerning the maximum velocity that ejecta might attain and the shape of the curves that trace the points of identical velocity magnitude have not been conclusively answered. These are appropriate questions to be studied in an experimental program. Typical sizes of the particles that result from small explosions should be found.

The most noticeable lack of data was for explosions near or at the surface level. Here studies can also be made on the effect that different shaped charges have on the ejecta.

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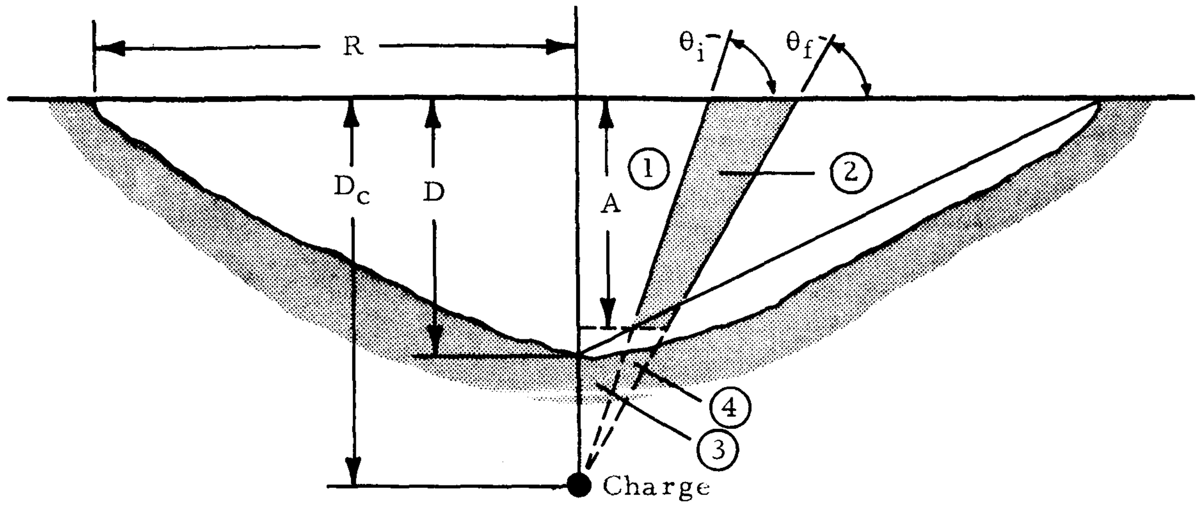
APPENDIX A

CALCULATION OF EJECTA VOLUME WHEN $D_c > D$



In order to find the volume of the shaded portion (Section 2), let height A be equal to y at the intersection of the two lines $y = -\tan\theta_i\, x + D_c$ and $y = -\frac{D}{R}\, x + D$. Eliminating x and letting y = A, it is found that

$$A = \frac{D\,(D_c - R\tan\theta_i)}{D - R\tan\theta_i}$$

$$V_2 = V_{1+2+3+4} - V_{3+4} - V_1$$

where V_i is the volume of the cone which includes the subscripted sections.

$$V_2 = V_{1+2+3+4} + V_3 - V_{3+4} - V_{1+3}$$

$$V_2 = \frac{\pi}{3}\,[D_c^2 \cot^2\theta_f\, D_c + (D_c - A)^2 \cot^2\theta_i\,(D_c - A) - (D_c - A)^2 \cot^2\theta_f\,(D_c - A) - D_c^2\,(\cot^2\theta_i)\,D_c]$$

$$V_2 = \frac{\pi}{3}\,(\cot^2\theta_f - \cot^2\theta_i)\,(3\,D_c{}^2\,A - 3\,D_c\,A^2 + A^3)$$

APPENDIX B

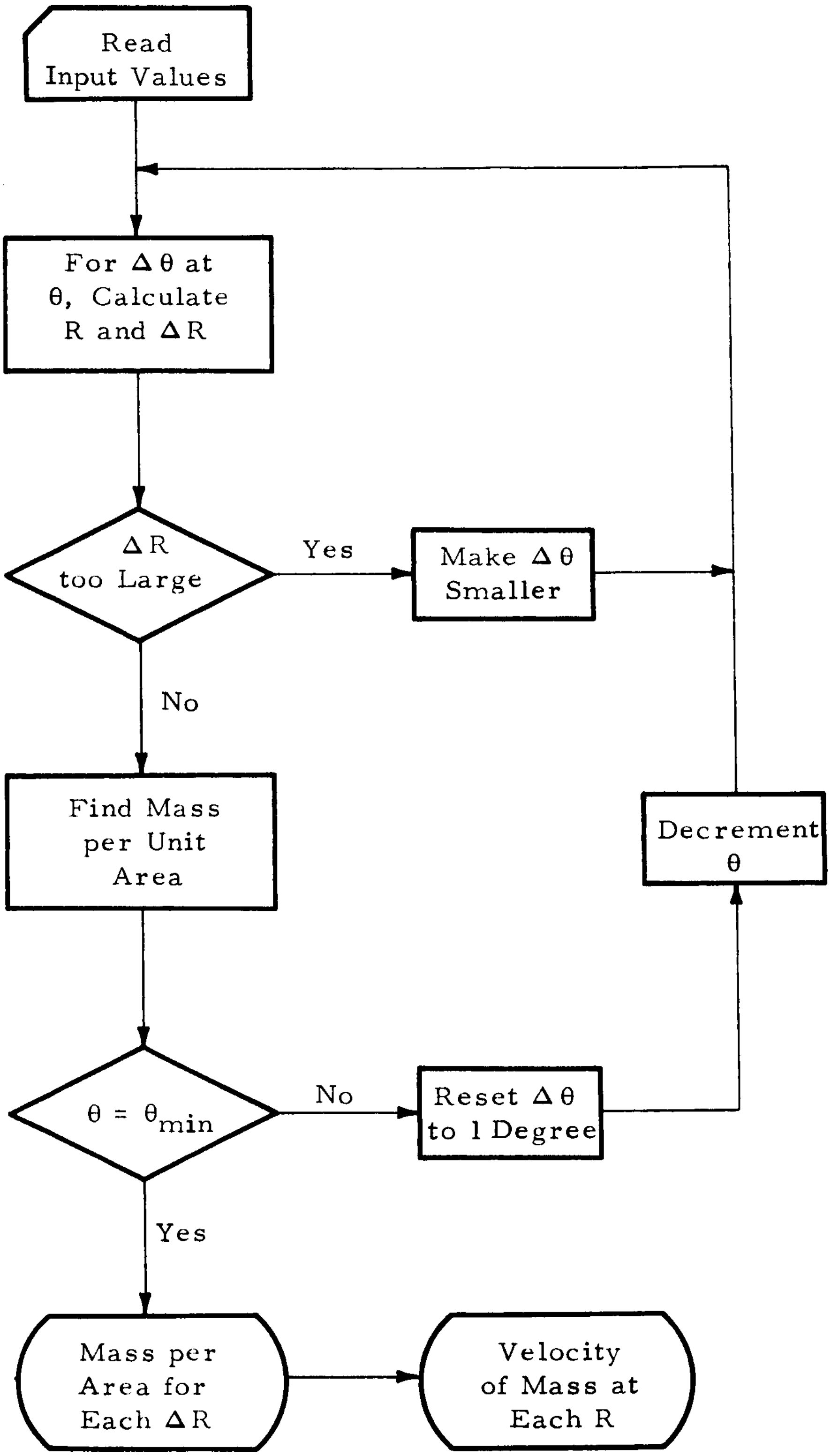
COMPUTER PROGRAM AND FORMATS

INPUT CARD

There is no limit to the amount of cases that can be run in succession. Each case occupies one input card with the following format:

Card Columns*		Description of Variable
1-10	D	crater depth in scaled feet
11-20	R1	crater radius in scaled feet
21-30	DC	charge depth in scaled feet
31-40	W	charge weight in pounds
41-50	RHO	lunar soil density (lb/ft^3)
51-60	AN	constant: n
61-70	A	constant: A
71-80	DELR	maximum range increment in feet (optional)

*Numbers may be placed anywhere in the number field. Decimal point must be included.



Flow Diagram for the Computer Program

COMPUTER PROGRAM LISTING

```
      DIMENSION R(3000),RF(3000),MPERA(3000),WT(3000),SAVMS(3000),
     XSVTHB(3000),THTB(3000),RAT(2),U(3000)
      REAL LMBD,MPERA,MPASV
      COT(X)=COS(X)/SIN(X)
      TAN(X) = SIN(X)/COS(X)
      DEG = 1./.01745329
      CHM = 1.5*.01745329
C  INSURES DIMENSIONS WILL NOT BE EXCEEDED
   20 LIM = 3000
C  READING SCALED CRATER DEPTH,SCALED CRATER RADIUS,SCALED CHARGE DEPTH
C  CHARGE WEIGHT,SOIL DENSITY,N,A,RANGE
      READ(5,100)D,R1,DC,W,RHO,AN,A,DELR
  100 FORMAT(8F10.0)
      KFLAG = 0.
C  FIND ANGLE CORRESPONDING TO MAXIMUM RANGE
      THMAX = 60.*.01745329
      LMBD = DC
      KF = 0
C  5.3002 FT/SEC SQ IS GRAVITATIONAL ACCELERATION CONSTANT
      CN1 = 2.*A **2/(5.3002*LMBD**(2.*AN))
      DC = DC*W**.33333333
      CALL SOLVR(DC,LMBD,THMAX,AN,A)
      RBMAX = CN1*SIN(THMAX)**(2.*AN+1.)*COS(THMAX)+COT(THMAX)*DC
      IF(DELR.NE.0.) GO TO 30
C  FIND MAXIMUM RANGE INCREMENT IF NOT READ IN
      DELR = RBMAX/10.
   30 CONTINUE
      WRITE(6,311) LMBD,W,D,R1,AN,A,RHO,DELR
  311 FORMAT(
     X31H1       CHARGE DEPTH                F7.3,10H SCALED FT/
     X30H        CHARGE WEIGHT              F8.3,4H LBS/
     X31H        CRATER DEPTH                F7.3,10H SCALED FT/
     X31H        CRATER RADIUS               F7.3,10H SCALED FT/
     X32H        CONSTANT-N                   F5.2/
     X30H        CONSTANT-A                 F7.2/
     X30H        LUNAR SOIL DENSITY         F6.1,12H   LBM/SQ FT/
     X29H        MAXIMUM RANGE INCREMENT F9.3,3H FT)
      D = D*W**.33333333
      R1 = R1*W**.33333333
      THST = 89.5*.01745329
C  FIND MINIMUM EJECTION ANGLE
      THTEND = ATAN(DC/R1)
      DELTH = .01745329
      THT = THST
C  FIND MINIMUM AND MAXIMUM RANGES ASSOCIATED WITH EACH CONICAL SHELL
      R(1) = CN1*SIN(THT)**(2.*AN+1.)*COS(THT)+COT(THT)*DC
      DO 1 I = 1,LIM
```

```
      KNTR = I
      THTF = THT-DELTH
    3 RF(I) = CN1*SIN(THTF)**(2.*AN+1.)*COS(THTF)+DC*COT(THTF)
      IF(KFLAG.EQ.1) GO TO 98
C   SPECIAL TREATMENT WITHIN 1.5 DEG OF MAXIMUM RANGE ANGLE
      IF(KFLAG.NE.2)GO TO 25
      KFLAG = 3
      GO TO 22
   25 CONTINUE
      IF(ABS(THT-THMAX).GT.CHM) GO TO 8
      IF(KF.NE.0) GO TO 11
      KF = 1
      GO TO 9
   11 IF(KF-2)12,13,2
   12 IF(R(I).NE.RF(I)) GO TO 2
      DELTH = .5*DELTH
      KF = 2
      GO TO 9
   13 DELTH = 2.*DELTH
      KF = 3
      GO TO 2
C   CHECK THAT MAXIMUM RANGE INCREMENT IS NOT EXCEEDED
    8 IF(ABS(R(I)-RF(I)).LE.DELR) GO TO 22
      DELTH = .8*DELTH
    9 THTF  =THT-DELTH
      GO TO 3
   98 KFLAG = 2
      GO TO 99
    2 IF(ABS(THT-THMAX).LE.CHM) GO TO 10
   22 DELTH = .01745329
   10 IF(KFLAG.GT.0) GO TO 99
      IF(THTF.GE.THMAX) GO TO 99
      IF(ABS(THT-THMAX).LT.1.E-04) GO TO 99
      DTHSV = DELTH
      DELTH = ABS(THTF-THMAX)
      THTF = THMAX
      KFLAG = 1
      GO TO 3
C   COMPUTE MASS/UNIT AREA DUE TO EACH CONICAL SHELL
   99 IF(DC.GT.D) GO TO 4
      MPERA(I) = .33333333*DC**3*(COT(THTF)**2-COT(THT)**2)/((RF(I)+R(I
     X))* ABS(RF(I)-R(I)))
      GO TO 5
    4 CN2 = (DC-R1*TAN(THT))/(D-R1*TAN(THT))
      MPERA(I) = .33333333*D*(COT(THTF)**2-COT(THT)**2)*CN2*(3.*DC**2-3.
     X*DC*D*CN2+D**2*CN2**2)/(ABS(RF(I)-R(I))*(RF(I)+R(I)))
    5 THTB(I) = .5*(THTF+THT)
      WT(I) = 0.
C   FIND VELOCITY OF CONICAL SHELL
      U(I) = A*(SIN(THTB(I))/LMBD)**AN
      R(I+1) = RF(I)
```

```
      THT = THTF
      IF(THTF.LE.THTEND) GO TO 6
    1 CONTINUE
      WRITE(6,350)
  350 FORMAT(69HODIMENSIONS HAVE BEEN EXCEEDED-TRY INCREASING MAXIMUM RA
     XNGE INCREMENT)
C   PREPARE COMPUTED DATA FOR PRINTOUT
    6 CONTINUE
      DO 7 I = 1,KNTR
      IF(R(I).LE.RF(I)) GO TO 7
      RSV = R(I)
      R(I) = RF(I)
      RF(I) = RSV
    7 CONTINUE
      KLIM = KNTR+1
      DO 80I = 1,KNTR
      KLIM = KLIM-1
      DO 80J = 1,KLIM
      IF(R(KLIM).GT.R(J)) GO TO 80
      RFSV = RF(J)
      RSV = R(J)
      THBSV = THTB(J)
      MPASV = MPERA(J)
      USV = U(J)
      RF(J) = RF(KLIM)
      R(J) = R(KLIM)
      THTB(J) = THTB(KLIM)
      MPERA(J) = MPERA(KLIM)
      U(J) = U(KLIM)
      RF(KLIM) = RFSV
      R(KLIM) = RSV
      THTB(KLIM) = THBSV
      MPERA(KLIM) = MPASV
      U(KLIM) = USV
   80 CONTINUE
      DO 301 J1 = 1,KNTR
      DO 302 J2 = J1,KNTR
      IF(RF(J1).LE.R(J2))GO TO 301
      WT(J2) = WT(J2)+MPERA(J1)
      IF(J2.EQ.J1) GO TO 302
      SVTHB(      J2) = THTB(J1)
      SAVMS(      J2) = MPERA(J1)
  302 CONTINUE
  301 CONTINUE
      KNT = KNTR-1
      DO 90I = 1,KNT
   90 RF(I) = R(I+1)
      KOUNT = 52
      DO110 K = 1,KNTR
      KOUNT = KOUNT+1
      IF(KOUNT.LT.53) GO TO 14
```

```
      WRITE(6,200)
      WRITE(6,201)
      WRITE(6,202)
      KOUNT = 0
   14 RAT(1) = MPERA(K)/WT(K)*100.
      THTB(K) = THTB(K)*DEG
      WRITE(6,203) R(K),RF(K),WT(K),RAT(1),U(K),THTB(K)
      RAT(2)  = SAVMS(K)/WT(K)*100.
      IF(WT(K).EQ.MPERA(K)) GO TO 110
      SAVU = A*(SIN(SVTHB(K))/LMBD)**AN
      SVTHB(K) = SVTHB(K)*DEG
      WRITE(6,204) RAT(2),SAVU,SVTHB(  K)
      KOUNT = KOUNT+1
  110 CONTINUE
      GO TO 20
  200 FORMAT(67H1            RANGE          MASS/AREA      PER CENT      VELOC
     XITY   ANGLE)
  201 FORMAT(66H             (FT)           LBM/SQ FT       MASS         FT/SE
     XC       DEG)
  202 FORMAT(1H0)
  203 FORMAT(XF10.4,XF10.4,E10.4,3XF10.3,2X2F10.3)
  204 FORMAT(35XF10.3,2X2F10.3)
      END
```

Subroutine SOLVR (DC, LMBD, THT, AN, A)

```
      REAL LMBD
      F(X) = (2.*AN+1.)*SIN(X)**(2.*AN+2.)*COS(X)**2-SIN(X)**(2.*AN+4.)-
     XCST
      FP(X)=(2.*AN+1.)*((2.*AN+2.)*SIN(X)**(2.*AN+1.)*COS(X)**3-2.*SIN(X
     X)**(2.*AN+3.)*COS(X))-(2.*AN+4.)*SIN(X)**(2.*AN+3)*COS(X)
      KOUNT = 0
      WRITE(6,1000)
      CST = DC*5.3002*LMBD**(2.*AN)/(2.*A*A)
    1 WRITE(6,200) THT
      THTP = THT-F(THT)/FP(THT)
      IF(ABS(THTP-THT)-.001)4,4,3
    3 THT = THTP
      KOUNT = KOUNT+1
      IF(KOUNT-30)1,1,6
    6 WRITE(6,220) THTP
  220 FORMAT(28H ITERATION DOES NOT CONVERGE,E14.7)
      CALL EXIT
    4 WRITE(6,200) THTP
      WRITE(6,1000)
      RETURN
  200 FORMAT(2XE14.7)
 1000 FORMAT(1H1)
      END
```

SAMPLE RUN

INPUT

CHARGE DEPTH	1.500 SCALED FT
CHARGE WEIGHT	64.000 LBS
CRATER DEPTH	1.190 SCALED FT
CRATER RADIUS	2.170 SCALED FT
CONSTANT-N	2.20
CONSTANT-A	95.00
LUNAR SOIL DENSITY	50.0 LBM/SQ FT
MAXIMUM RANGE INCREMENT	14.551 FT

OUTPUT

RANGE (FT)		MASS/AREA LBM/SQ FT	PER CENT MASS	VELOCITY FT/SEC	ANGLE DEG
5.0429	15.1023	.2146-03	100.000	38.920	89.000
15.1023	25.0837	.2171-03	100.000	38.881	88.000
25.0837	30.6212	.2213-03	100.000	38.816	87.000
30.6212	33.1530	.1953-01	98.867	11.461	35.000
			1.133	38.816	87.000
33.1530	34.9356	.2595-01	99.147	12.095	36.000
			.853	38.816	87.000
34.9356	35.9220	.2596-01	.876	38.725	86.000
			99.124	12.095	36.000
35.9220	38.9269	.2562-01	99.113	12.739	37.000
			.887	38.725	86.000
38.9269	42.1637	.2304-01	99.013	13.393	38.000
			.987	38.725	86.000
42.1637	44.6076	.1994-01	98.860	14.055	39.000
			1.140	38.725	86.000
44.6076	45.6269	.1995-01	1.180	38.608	85.000
			98.820	14.055	39.000
45.6269	49.3084	.1699-01	98.614	14.726	40.000
			1.386	38.608	85.000
49.3084	53.1979	.1438-01	98.363	15.403	41.000
			1.637	38.608	85.000
53.1979	54.0508	.1217-01	98.065	16.086	42.000
			1.935	38.608	85.000
54.0508	57.2825	.1218-01	2.019	38.466	84.000
			97.981	16.086	42.000
57.2825	61.5472	.1034-01	97.622	16.774	43.000
			2.378	38.466	84.000
61.5472	63.2180	.8825-02	97.214	17.467	44.000
			2.786	38.466	84.000
63.2180	65.9743	.8838-02	2.930	38.298	83.000
			97.070	17.467	44.000
65.9743	70.5438	.7593-02	96.589	18.163	45.000
			3.411	38.298	83.000
70.5438	72.0640	.6573-02	96.060	18.862	46.000
			3.940	38.298	83.000
72.0640	75.2333	.6589-02	4.177	38.105	82.000
			95.823	18.862	46.000
75.2333	80.0181	.5752-02	95.216	19.562	47.000
			4.784	38.105	82.000
80.0181	80.5463	.5065-02	94.567	20.262	48.000
			5.433	38.105	82.000
80.5463	84.8714	.5085-02	5.805	37.887	81.000
			94.195	20.262	48.000

RANGE (FT)		MASS/AREA LBM/SQ FT	PER CENT MASS	VELOCITY FT/SEC	ANGLE DEG
84.8714	88.6249	.4521-02	93.471	20.962	49.000
			6.529	37.887	81.000
88.6249	89.7641	.4546-02	7.034	37.644	80.000
			92.966	20.962	49.000
89.7641	94.6655	.4083-02	92.168	21.661	50.000
			7.832	37.644	80.000
94.6655	96.2631	.3703-02	91.363	22.358	51.000
			8.637	37.644	80.000
96.2631	99.5430	.3733-02	9.379	37.377	79.000
			90.621	22.358	51.000
99.5430	103.4275	.3422-02	89.770	23.051	52.000
			10.230	37.377	79.000
103.4275	104.3626	.3460-02	11.206	37.086	78.000
			88.794	23.051	52.000
104.3626	109.0890	.3208-02	87.913	23.740	53.000
			12.087	37.086	78.000
109.0890	110.0880	.3006-02	87.101	24.425	54.000
			12.899	37.086	78.000
110.0880	113.6860	.3053-02	14.242	36.772	77.000
			85.757	24.425	54.000
113.6860	116.2186	.2896-02	84.984	25.103	55.000
			15.016	36.772	77.000
116.2186	118.1165	.2956-02	16.734	36.434	76.000
			83.266	25.103	55.000
118.1165	121.7969	.2839-02	82.578	25.774	56.000
			17.422	36.434	76.000
121.7969	122.3432	.2916-02	19.606	36.074	75.000
			80.394	25.774	56.000
122.3432	126.3285	.2839-02	79.858	26.438	57.000
			20.142	36.074	75.000
126.3285	126.8048	.2801-02	79.587	27.092	58.000
			20.413	36.074	75.000
126.8048	130.0351	.2903-02	23.204	35.692	74.000
			76.796	27.092	58.000
130.0351	131.2281	.2909-02	76.846	27.737	59.000
			23.154	35.692	74.000
131.2281	133.4263	.3047-02	26.641	35.289	73.000
			73.359	27.737	59.000
133.4263	135.0569	.3107-02	73.871	28.372	60.000
			26.129	35.289	73.000
135.0569	136.4661	.3302-02	30.500	34.864	72.000
			69.500	28.372	60.000
136.4661	138.2855	.3434-02	70.673	28.995	61.000
			29.327	34.864	72.000
138.2855	139.1198	.3726-02	34.857	34.419	71.000
			65.143	28.995	61.000

RANGE (FT)		MASS/AREA LBM/SQ FT	PER CENT MASS	VELOCITY FT/SEC	ANGLE DEG
139.1198	140.9121	.3968-02	67.270	29.606	62.000
			32.730	34.419	71.000
140.9121	141.3543	.4439-02	39.873	33.954	70.000
			60.127	29.606	62.000
141.3543	142.9393	.4876-02	63.695	30.204	63.000
			36.305	33.954	70.000
142.9393	143.1383	.5745-02	45.941	33.470	69.000
			54.059	30.204	63.000
143.1383	144.3736	.6596-02	59.990	30.788	64.000
			40.010	33.470	69.000
144.3736	144.4426	.8659-02	54.299	32.968	68.000
			45.701	30.788	64.000
144.4426	145.2254	.1075-01	56.244	31.357	65.000
			43.756	32.968	68.000
145.2254	145.2406	.2105-01	71.286	32.447	67.000
			28.714	31.357	65.000
145.2406	145.5085	.3178-01	52.781	31.908	65.997
			47.219	32.447	67.000
145.5085	145.5085	.1037+01	98.382	32.179	66.497
			1.618	31.908	65.997

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13. ABSTRACT

This report determines impact densities and velocity distribution of the debris resulting from explosions on the lunar surface. Consideration is given to the type of soil that will give the best empirical data. Crater volumes and shapes are predicted, and the ejecta patterns determined are based on radial ejection of material from the charge center.

14. KEY WORDS
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