CONF-790218--1

LA-UR-79-88

MASTER

TITLE: EMPIRICAL CHARACTERIZATION OF OIL SHALE FRAGMENTATION EXPERIMENTS

AUTHOR(S): S. C. Schmidt
C. L. Edwards
R. Oliver
J. N. Johnson
P. Wapner

SUBMITTED TO: Paper to be presented at the Fifth Annual Conference on Explosives and Blasting Technology, St. Louis, MO, February 7-9, 1979

los alamos scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

Form No. 836
St. No. 2629
1/75

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

EMPIRICAL CHARACTERIZATION OF OIL SHALE FRAGMENTATION EXPERIMENTS

by

S. C. Schmidt, C. L. Edwards, J. N. Johnson and R. Oliver

Los Alamos Scientific Laboratory
Los Alamos, NM 87544

and

P. Wapner

Rio Blanco Oil Shale Co.
Denver, CO

9504121

ABSTRACT

Shale oil recovery rates that can be achieved in underground *in situ* retorts can be strongly influenced by the shale breakage and fragment-size distribution achieved during rubblization. Since the fragmentation pattern in the retort is a direct result of the blast design used for rubblization, the characterizing blast parameters should be carefully selected. Explosives should be matched to the host material and blast geometries properly chosen so that the required fragmentation results are achieved at optimum costs. Special attention must be directed to selecting blast parameters that produce uniform bed permeability, suppression of fines, proper fragment size distribution, and minimal damage to the retort walls and ceiling. The influence of joints and natural fractures should also be known. In instances where the requisite blasting parameters are unknown, they should be determined from test blasts.

Small and intermediate size cratering and bench blast experiments are being made to determine critical depths, volume crater constants, and fragment-size distribution scaling constants for Piceance Creek Basin oil shale. The small tests are made using PETN explosive in meter-sized blocks. The intermediate-size tests are on the ten-to-twenty foot scale using an ANFO explosive. The experiments are designed to investigate the adequacy of using empirical scaling laws to describe the influence of bedding plane orientation, burden distance, explosive energy release, and borehole diameter on blast results. Crater volumes, sieved fragment-size distributions, free surface velocities, and explosive detonation velocities are measured. Data are treated using a "Livingston type" performance evaluation based on explosive volume to determine critical and optimum depths. Measured fragment-size distributions are interpreted using empirical scaling techniques.

Illustrations and figures at end of paper.

similar to that developed by Bergmann, et al. of Dupont de Nemours and Company.

INTRODUCTION

One of the larger known sources of petroleum lies in the oil bearing shale beds scattered throughout the world. The technology of extracting the oil from these resource beds has received considerable attention over the past 100 years.[1] Generally, the recovery scheme used has been one of mining the shale using conventional techniques and then hauling the shale to processing plants located on the surface. This scheme was used by the US Bureau of Mines[2] and more recently by the Department of Energy at its Anvil Points experimental facility in the Piceance Creek Basin near Rifle, CO, and is also being considered for a 20,000 barrel per day plant to be located in Israel. A second technique for recovering oil from the shale, which may prove to be a more economical option for deeper lying shale beds such as occur in the Piceance Creek Basin of Colorado, is by underground *in situ* processing. Here a controlled chemical reaction, in the form of a low temperature burn front passing through the shale bed, pyrolysizes the oil lying in advance of the burning region. The liquid product is collected and transported to the surface. In order for *in situ* techniques to work, the permeability of the native rock must be increased to allow for the fluid flow necessary to maintain the burn front and recover the product. Enhanced permeability requires either an increase in the porosity of the rock or the creation of large, properly spaced fractures.

Two techniques of *in situ* processing exist: true *in situ* and modified *in situ*. In the true *in situ* scheme, the natural formation is stimulated from a well bore by either hydrofracturing or by an explosive charge. Linking can then occur between adjacent wells, and a burn front initiated at one well will progress along the zone of increased permeability. A difficulty of the true *in situ* technique is that as a result of the confinement experienced at depths, it is difficult to displace the rock sufficiently to create the void volume required for the desired permeability increase. The modified *in situ* scheme, by removing some of the shale by mining for surface processing prior to explosive fracture, allows the damaged rock to expand into the mined-out volume thus increasing the permeability of the resultant rubble pile sufficiently to allow pyrolysis and removal of retorted products without excessive compressor costs. Void volumes achieved can be controlled by the amount of mining with 20% - 30% being a representative number. In addition to increasing the void volume of the resource bed, the *in situ* oil shale retort should also have the following characteristics: (a) A particle-size distribution throughout the retort volume that peaks in the range required for maximum extraction efficiency. Current chemical kinetics and process studies place this range at roughly 5 - 50 cm with the peak around 10 cm. The amount of fines produced in the rubblization process must be minimal in order to avoid plugging the paths through which the gases and other products must move. This may be the most important single factor to control, (b) Uniform void distributions in both the horizontal and vertical sense in order to achieve a stable flame front and avoid channeling, and (c) A rubblized volume that is well defined with maximum residual wall and roof integrity in order to provide retort stability, containment of combustion products, safety for workers in adjacent areas, prevention of water influx, and maximum utilization of the resource. These characteristics require that the mining and blasting phase of the retort bed preparation be well designed.

The explosive technology for rock fragmentation is very old and quite well known. Historically, it has not been necessary to exercise great control over explosive events in rocks, since processing has been done on the surface. However, the proper fragmentation *in situ* of an oil shale retort introduces the previously stated new requirements on the blast geometry and on the fragmentation results. To augment existing blasting and explosive technology, and hopefully provide insight to some of the problems posed, we are engaged in a research program directed toward gaining a better understanding of explosive events. The scope of this effort ranges from constructing a predictive dynamic rock fragmentation hydrodynamic computer code, calibrated by using highly instrumented test shots in an oil shale mine, to using proven empirical scaling techniques. This work reports results of some small field and laboratory-sized test blasts designed to empirically characterize explosive events in oil shale. These tests are part of an ongoing effort to gain information, which will aid in the design and preparation of commercial oil shale retorts.

BLAST CHARACTERIZATION

Numerous techniques exist for empirically characterizing explosive rock fragmentation events.[3] Generally, these formulations are calibrated to describe a particular geometry in a particular host medium for a specified range of stimulation or explosive loading. Extending the results beyond the scope of the calibration is risky and may even be incorrect, consequently, each new application such as the controlled fragmentation of oil shale *in situ* requires additional experimentation. To describe the explosive fracture of oil shale, we have chosen three of the many possible empirical scaling techniques: crater blast theory, fragment-size distribution measurements, and burden velocity correlations. These choices are not meant to exclude other methods nor may they be the best ones. They are simply what we have selected to use for our initial evaluation of some small-field and laboratory-sized test blasts. The test blasts are being made with three objective in mind. We are interested in providing design information for and evaluating proposed oil shale retort blasting schemes, evaluating scaling as a tool to infer the behavior of large-scale blast configurations from small-scale experiments, and to test and calibrate numerical hydrodynamic computer codes that describe explosive rock fragmentation events. The influence of bedding plane orientation, the natural joints and fractures of the shale, and explosive tailoring are also being investigated.

The Livingston theory for the description of crater blast has received wide usage for comparing the rock breakage performance of explosives. C. H. Grant[5] modified the original formulation somewhat by changing the cratering formula from one based on explosive weight to an explosive volume basis, $N = \Sigma v^{1/3}$. This replaced the strain energy factor used by Livingston with a new constant, Σ, called the volume crater constant. v and N are the explosive volume and the critical crater depth, respectively. The critical depth has its usual interpretation of how far down in a blast hole a given weight or volume of explosive can be detonated and still pull rock at the surface. By comparing explosives on a volume standard instead of a weight basis, Grant was able to nullify the effects of performance variations from changes in geometry. For this same reason, we have also chosen to use the volume based cratering formulation. Grant also evaluated crater formation in terms of a reduced crater curve. By expressing the charge burial depth and the cratering volume as ratios to the critical depth and the critical depth cubed, the results of different explosives and host materials could be described to some extent using a single curve. This reduced considerably the number of experiments required to define a complete cratering curve. It should be noted, however, that the results of other workers[6] using several explosives and host materials suggest this description may not be the correct one for oil shale. We have nevertheless attempted to apply Grant's formulation and results to small-field and laboratory-sized shots in oil shale. The results to date are presented in the next section.

The methods devised by Bergmann, et al.[7] are being used to describe the fragmentation achieved. To apply this technique to cratering shots and multiple-borehole, time-sequenced bench shots, requires some modification of the functional in the scaled average fragment-size term. An empirical alteration has been made for bench blasts in granite, limestone, and sandstone using data published by Bergmann, et al.[8] In Bergmann's empirical fragmentation equation, $F = A - C \ln T$, A and C are constants that reflect the material response. F, the scaled average fragment size, and T, the blast condition term are given by

$$F = \frac{F_m \left[\frac{1}{B^3} + \frac{1}{L^3} + \frac{1}{S^3} \right]^{1/3}}{\left[1.23 - 0.12\ (S/B) \right] \left[0.6 + 0.4/(1 + D/S)^2 \right]} , \qquad (1)$$

and

$$T = \left[0.36 + \rho e \right] \frac{D_e^{\,2}}{\left[1 - \frac{D_e}{V} + \frac{D_e^2}{V^2} \right]^{4/3}} \frac{1}{R} \frac{W}{B^2} . \qquad (2)$$

F_m is the measured average fragment size, B is the borehole burden distance, L is the charge length in the borehole, S is the borehole spacing so S/B represents the spacing-to-burden ratio, and D is the delay time between successive borehole firings. In the blast condition term, ρe is the explosive density, D_e the explosive detonation velocity, W, a term that represents the work done by the explosive, V is the sonic velocity in the host material, and R is the borehole decoupling ratio. The applicability of this scaling for oil shale in both field and laboratory-sized geometries is being determined. Previous results[9] have indicated that direct scaling from field to laboratory experiments is difficult. For cratering shots, a similar type of scaling is also being pursued; however, since the fragmentation distribution has only been estimated for one small field test, a formulation now is premature.

A third way of looking at cratering shots will be to correlate the burden velocity measured at the surface with a scaled depth of burial. Redpath[10] presents the results of several authors for this kind of comparison. To date, we have not determined burden velocities for either the small field or laboratory experiments; however, these measurements are planned for the immediate future.

EXPERIMENTS

As stated previously, two kinds of experiments are in progress: small field experiments being conducted in the Colony Mine near Rifle, CO, and laboratory tests in meter-sized blocks of oil shale being done at Los Alamos, NM. To date, three field shots, each using 5.2 kg of ANFO in a 4 1/4 in. diam. borehole, have been fired in approximately 2 gm/cm^3 density oil shale. The charge aspect ratio was six. Each shot was stemmed both above and below the charge with oil shale fragments averaging approximately 1 in. in size, and was initiated at the bottom of the charge with a blasting cap and an Atlas Type G booster. For Shot #1, the borehole was in the mine floor and consequently perpendicular to the bedding planes. The charge center of gravity was approximately 5.3 ft. below the free surface. Subsequent to blasting, the apparent crater was excavated to determine both the size and shape of the true crater. Fig. 1 shows the profiles measured across the crater in two perpendicular directions. The general features noted from excavation are: the bottom of the crater cone appeared to form near the top of the charge, the borehole diameter in the vicinity of the charge, labeled B, increased to approximately 10 in., and surface heaving and fracturing occurred at distances of 15 - 20 ft. from the location of the borehole. This feature, which is not shown in Fig. 1, probably resulted from a combination of surface spall and heaving due to the late time gas generation of the ANFO explosive. Also, the shale was partially fractured near most of the crater walls, but was not easily removable. The crater volume given in

Table I was estimated by adding the volumes of 6 in. thick disks located perpendicularly along the borehole.

Table I. Field Crater Shot Dimensions

Shot Number	Burial Depth (ft.)	Crater Volume (ft.)^3	Scaled Burial Depth	Scaled Crater Volume	Average Fragment Size (in.)
1	5.3	198	0.48	0.15	11
2	7.3	231	0.66	0.17	-
3	7.3	242	-	-	-

The radius of each disk was determined by averaging the radii from each of the four profile directions. The region denoted E in Fig. 1 represents highly fragmented, but unexcavated rock, which was included in the volume calculation. The fragment-size distribution of the rubble from Shot #1 was crudely determined by placing the muck removed into five piles, each of a different size range, and then estimating the weight of each pile. These results, given in Table II, indicate the average fragment size is approximately 11 in. and that a fair number of fines were created.

Table II. Fragment Size Distribution, Field Shot #1

Size Range (in.)	Cumulative Weight (lbs.)	Cumulative Weight (%)
0 - 6	4,019	21
6 - 12	8,361	44
12 - 18	11,523	60
18 - 24	15,723	82
> 24*	19,195	100

*This was one large boulder approximately 3.3 ft. x 3.3 ft. x 2.5 ft.

The total weight was approximately 20% less than that expected from the crater volume estimate, thus indicating probably both a loss of material during collection and an error in the measurements and analysis.

Shot #2 differed from Shot #1 only in that the charge center of gravity was lowered from 5.3 ft. to 7.3 ft. below the free surface; however, the postshot appearance of the crater formed was radically different from the results of Shot #1. Figs. 2 and 3 show the highly asymmetric crater shape found after excavation. E, in Fig. 2, indicates a large depression, apparently the result of the explosive gases venting through a fracture or joint present in the material prior to blasting. The region in the 3 direction then appears to have been preferentially heaved. On the opposite side of the crater, in the 4 direction, the oil shale has not been blasted free, but has been fractured; however, the extent of the fractured region is not known. The question which is of particular interest here is "Would this region have blasted free in a multiple-borehole shot?" Also, the influence of the VUGS observed, labeled D in Fig. 2, is not known although it is suspected they would reduce the heaving effect of the explosive gases. As in Shot #1, the borehole diameter in the vicinity of the explosive increased to about 10 in., surface heaving and fracture occurred as far as 15 ft. to 20 ft. from the borehole, and the bottom of the crater cone formed near the top of the explosive charge. A previous shot, whose borehole bottom is labeled G in Fig. 3, does not appear to have affected the rock in the vicinity of the test borehole. Even though the crater formed was highly asymmetric, its volume, given in Table I, was estimated using the method described for Shot #1. A fragment-size distribution was not determined for Shot #2.

Shot #3 was similar to Shot #2, only the borehole was located in the mine wall so that it ran along the bedding planes. Fig. 4 shows the measured crater profiles for the vertical and horizontal directions. Since the free surface location was not measured prior to blasting, it has been approximated by extending a line from one edge of the crater to the opposite edge, labeled C in Fig. 4. The general appearance is similar to Shot #1 with the exception that the shale removed along the horizontal direction may be somewhat larger than in the vertical direction. Because the crater profile measurement is approximate and this is the result of a single shot, caution is urged in accepting this result. This observation is not inconsistent with studies of stress wave propagation in anisotropic material[11] and modeling work done using plastic laminates.[12] The crater volume, again estimated using the technique described for Shot #1, is given in Table I.

Using the results of Shots #1 and #2, and Grant's[9] single cratering curve as an aid, the critical cratering depth was estimated to be 11 ft. The scaled depth of burial and crater volume were determined (given in Table I) and the results plotted on the reduced crater volume curve shown in Fig. 5. Grant's single cratering curve is also shown for comparison. While the critical depth determined seems reasonable, it is not definitive from the two data points that Grant's single curve will correctly describe these oil shale experiments. Additional shots designed to more succinctly determine the curve shape and critical depth are in progress. A volume crater constant, Σ, of 1.5 ft./in. was calculated using a critical depth of 11 ft. and an explosive volume of 363 in.^{3}.

Laboratory tests have been conducted using PETN explosives in meter-sized blocks of oil shale. As stated earlier, the primary purpose of these experiments was to evaluate the concept of modeling field-sized blasts using laboratory-sized blocks. We have been led to believe from several sources that this kind of scaling is extremely difficult; however, since the rewards of finding a successful correlation are great, we feel an effort is warranted. Reported here are the results of three crater blasts and one multiple-hole bench blast. All of the crater shots are with 0.9 gm/cm^3 density PETN and with borehole diameters of 1/4" and charge lengths of 1 1/2". The charge aspect ratio is six, similar to that in the field experiments. Shots #1 and #2 were stemmed with beach sand and initiated at the bottom of the charge with a Reynolds RP 87 detonator. Table III shows the charge burial depths and the resulting crater volumes.

Table III. Laboratory Cratering Dimensions

Shot Number	Burial Depth (ft.)	Crater Volume (ft.)^3	Scaled Burial Depth	Scaled Crater Volume
1	.34	.06	.54	.24
2	.67	0	1.06	0
3	.40	.18	.63	.72

Note that for Shot #2, the volume is zero, indicating that the charge was placed below the critical depth.

For Shot #3, the borehole was drilled from the bottom of the block to within 4 in. of the free surface. The charge was then loaded and the borehole stemmed with beach sand; consequently, the region between the top of the charge and the free surface was undisturbed oil shale. As can be seen in Table III, the crater volume obtained with Shot #3 is considerably larger than that obtained for Shot #1, even though the charge burial depths are similar. Presumably the difference in stemming is responsible for this behavior; however, caution must be urged in accepting this result on the basis of one shot. Additional experiments are planned.

If the volume crater constant Σ, equal to 1.5 ft./in., determined for the small field tests is used along with the PETN charge volume of 0.074 $in.^3$ to estimate the critical depth for the laboratory experiments, N is found to be 0.63 ft. Using this value for N, the scaled burial depth and scaled crater volume have been determined and are shown in Table III and by the crosses in Fig. 5 for Shots #1 and #2. The results agree quite well with results of the small-field tests and Grant's single cratering curve.

The purpose of the bench shot was to explore the possibility of using the fragmentation scaling technique developed by Bergmann, et al.[10] and modified as discussed previously to describe explosive events in oil shale. The shot was fired using five 7 in. deep boreholes with spacing and burden distances of 3.9 in. Each borehole was filled with 6 in. of 0.41 gm/cm^3 density PETN and then stemmed with beach sand. All five charges were initiated simultaneously from the top using Reynolds RP 87 detonators. The shot behaved similar to a presplit blast. The fragment size distribution measured (Table IV) gave an average fragment size of 4.3 in. Using Eqs. (1) and (2) with previously given geometrical parameters, D_e = 3.4 km/sec, V = 3.5 km/sec, R = 1, and W $\sim$ 1.4 kcal/gm, F and T were computed to be 1.5 and 0.28, respectively. This result is shown in Fig. 6 along with the fragmentation scaling curves reported previously by Bergmann, et al.[10] for experiments in meter-sized blocks of granite, limestone, and sandstone. Additional bench experiments in the laboratory and in the field are not planned for the immediate future, since the cratering geometry is currently of more interest for the fragmentation of oil shale retorts.

Table IV. Fragment-Size Distribution, Laboratory Bench Shot

Size Range (in.)	Cumulative Weight (lbs.)	Cumulative Weight (%)
1	11.4	13
2	17.5	20
3	26.3	30
4	35.9	41
5	62.1	71
6	87.5	100

SUMMARY

In conclusion, for cylindrical ANFO 4 1/4" diam. charges in oil shale and for geometrically similar 1/4" diam. PETN charges also in oil shale, we have made an initial estimate of 1.5 ft./in. for the volume cratering constant. There appears to be some possibility of scaling between the two different sized experiments; however, additional confirming data are required. A measurement of the fragment-size distribution for one field test indicates an average fragment size of 11 in. One field test has demonstrated that existing joints or fractures in the shale can drastically alter the crater shape for single-borehole shots. It is suggested that the anisotropy introduced by drilling the borehole parallel to the bedding planes can influence the crater shape.

In continuing studies, we are hoping to investigate the effect of different explosives on shale breakage, particularly on the number of fine fragments produced, the results obtained using multiple borehole crater shots and the influence of natural joints and fractures on the fragmentation, the effect on shale removal when blasting to a confined volume, and the possibility of using precision time-sequenced charge initiation.

ACKNOWLEDGMENTS

The work reported here was performed under US Department of Energy Contract No. W-7405-ENG. 36, Office of Fossil Energy. The authors also wish to express their appreciation to the personnel of the Atlantic Richfield Company and, in particular, to Ki Bianchi at the Colony Mine for their assistance with these experiments.

REFERENCES

1. R. H. McKee, Shale Oil, (The Chemical Catalog Co., Inc., New York, 1925).

2. P. G. Zambas, G. R. Haworth, F. W. Brackebusch, and J. B. Sellers, "Large Scale Experimentation in Oil Shale," Transactions of Society of Mining Engineers 252, 285 (September 1972).

3. For example: U. Langefors and B. Kihlström, Rock Blasting, (John Wiley and Sons, Inc., New York, 1963), or S. M. Johnson, "Explosive Excavation Technology," Technical Report 21, US Army Engineer Waterways Experiment Station Explosive Excavation Research Laboratory, Livermore, CA (June 1971).

4. C. W. Livingston, "Fundamental Concepts of Rock Failure," Quarterly of The Colorado School of Mines 51, 3 (July 1956).

5. C. H. Grant, "Simplified Explanation of Crater Method," Engineering and Mining Journal 165, 11, 86 (November 1964).

6. A. Bauer, G. R. Harris, L. Lang, P. Preziosi, and D. J. Sellect, "How IOC Puts Crater Research to Work," Engineering and Mining Journal 166, 9, 117 (September 1965).

7. O. R. Bergmann, J. W. Riggle, and F. C. Wu, "Model Rock Blasting - Effect of Explosives Properties and Other Variables on Blasting Results," Int. Jour. Rock Mech., Min. Sci. and Geomech. Abstr. 10, 585 (1973).

8. O. R. Bergmann, F. C. Wu, and J. W. Edi, "Model Rock Blasting Measures - Effect of Delays and Hole Patterns on Rock Fragmentation," Engineering and Mining Journal 175, 6, 124 (June 1974).

9. C. H. Noron and D. D. Porter, "A Comparison of Theoretical Explosive Energy Measured Under Water with Measured Rock Fragmentation," Proc. 3rd Int. Cong. Rock Mech., Denver, CO (1974).

10. B. B. Redpath, "Application of Cratering Characteristics to Conventional Blast Design," 17th US Symposium on Rock Mechanics, Snowbird, UT (August 1976), Session 5B.

11. J. K. Dienes, J. L. Norton, H. M. Ruppel, and L. G. Margolin, "The Effect of Anisotrophy on the Fragmentation of Oil Shale in Explosively Produced Fracture of Oil Shale," Los Alamos Scientific Laboratory report LA-6817-PR (September 1977).

12. C. J. Konya, "The Effects of Joints and Bedding Planes on Rock Blasting," preprint.

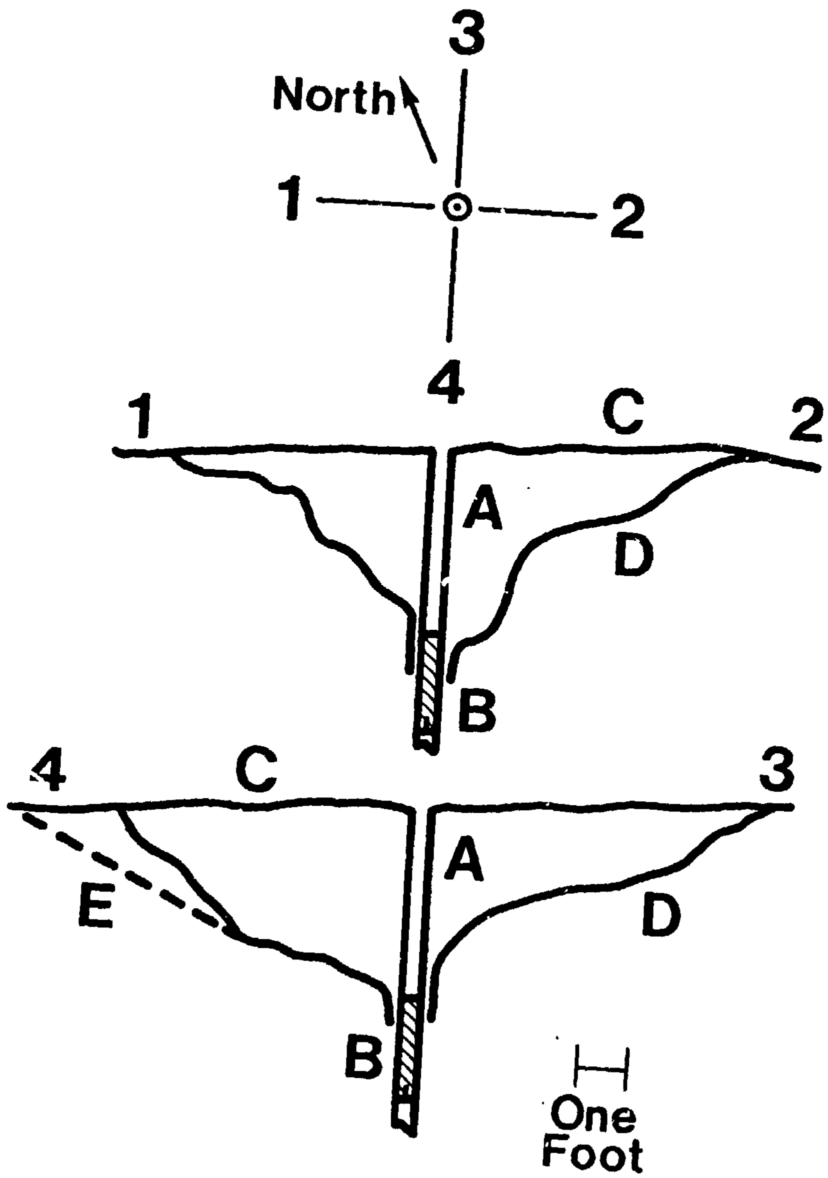

Fig. 1. Profile, Field Crater Shot #1. A - Borehole, B - Explosive charge, C - Original mine floor profile, D - Crater profile after blasting, E - Fragmented rock not removed.

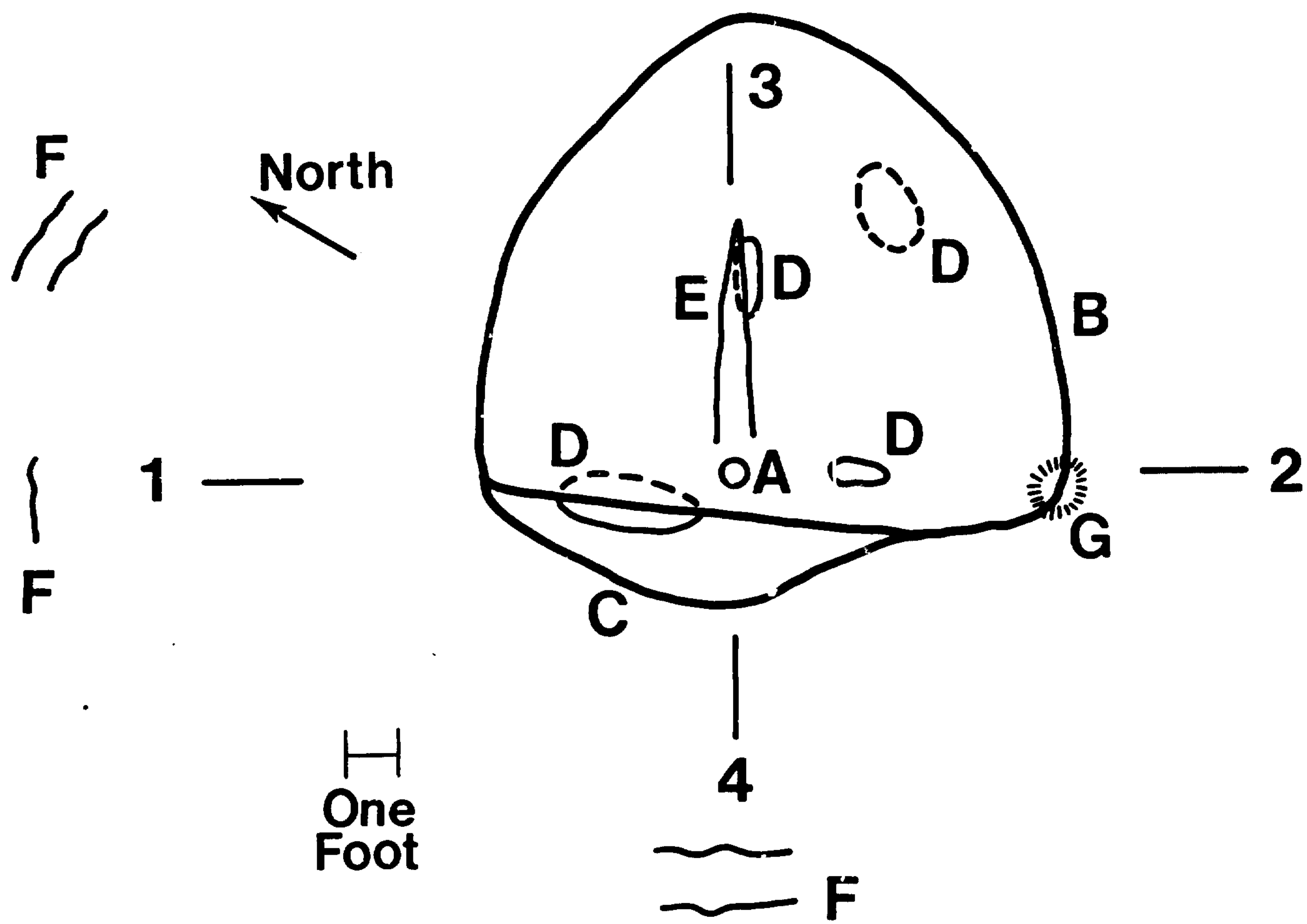

Fig. 2. Surface Plan, Field Crater Shot #2. A - Borehole, B - Crater surface radius, C - Highly fractured, slightly removed, shale, D - VUG locations, E - Depression at crater bottom, F - Regions of surface fracturing and heaving, G - Previous shot borehole bottom.

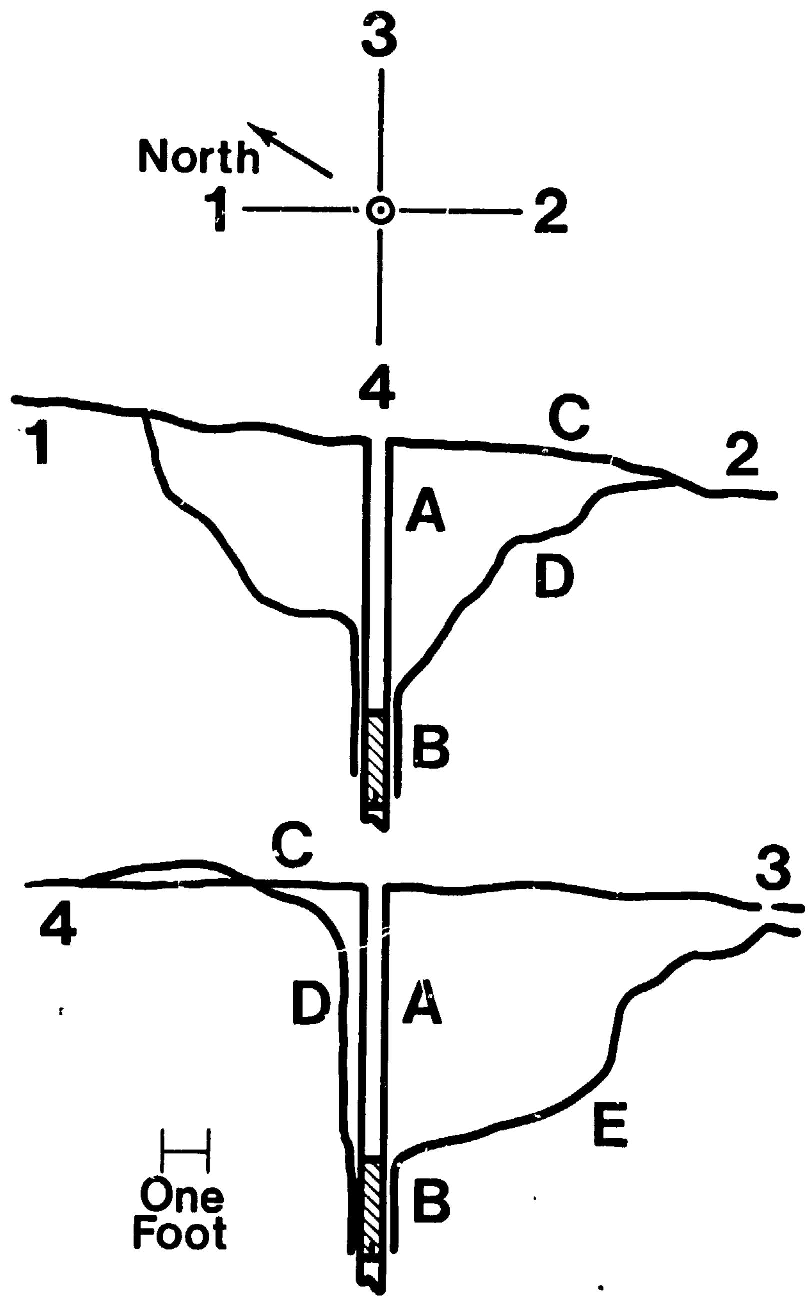

Fig. 3. Profile, Field Crater Shot #2. A - Borehole, B - Explosive charge, C - Original min floor profile, D - Crater profile after blasting, E - Depression at crater bottom.

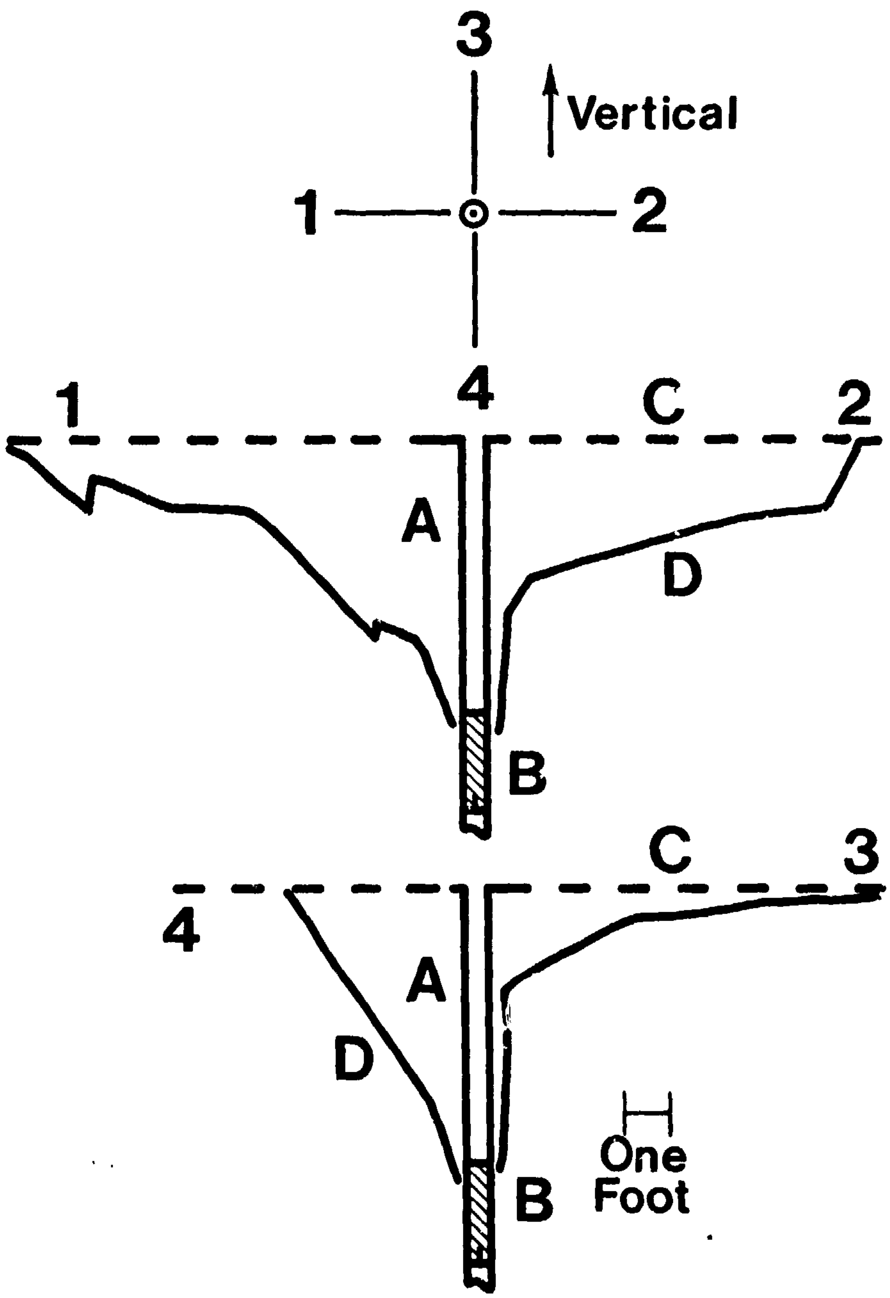

Fig. 4. Profile, Field Crater Shot #3. A - Borehole, B - Explosive charge, C - Approximate mine wall location before blasting, D - Crater profile after blasting.

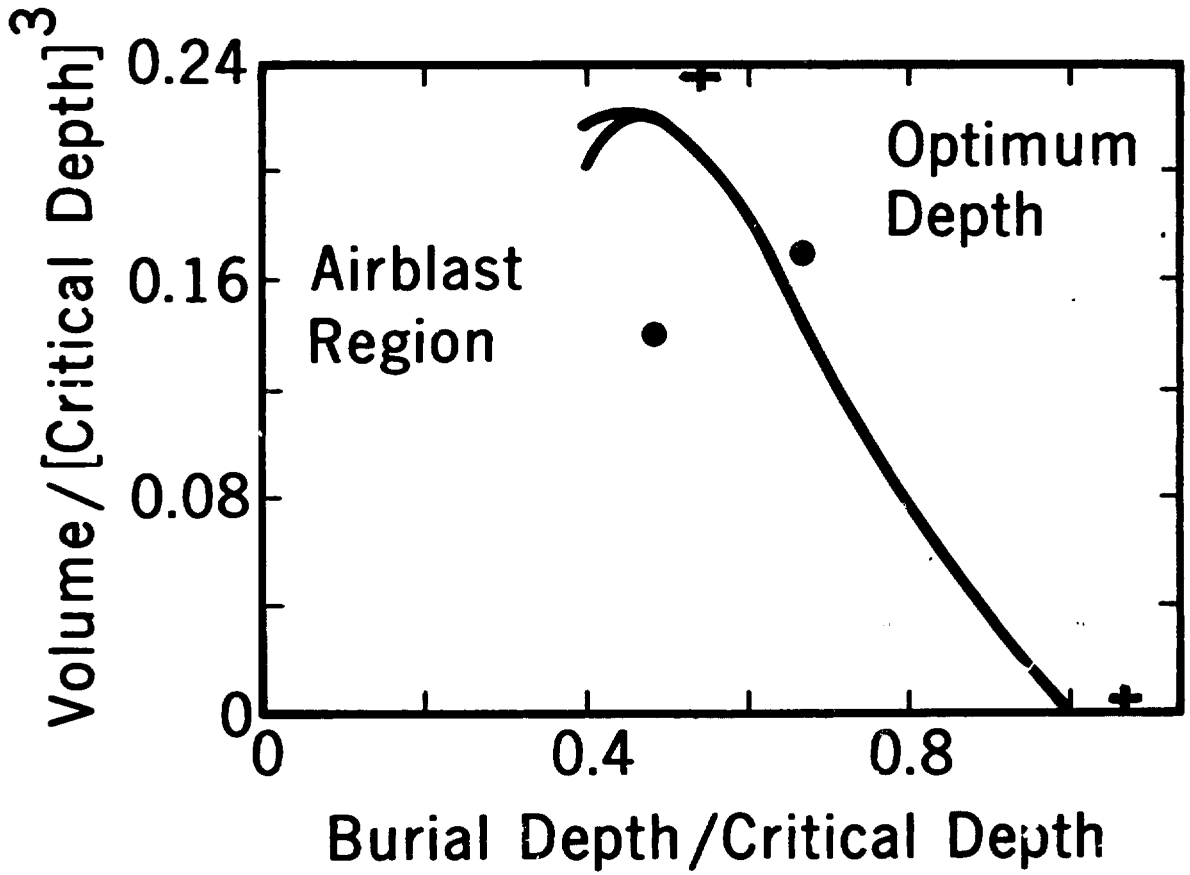

Fig. 5. Reduced Crater Curve. • - Field Shots, + - Laboratory shot, — - Grant's reduced crater curve.

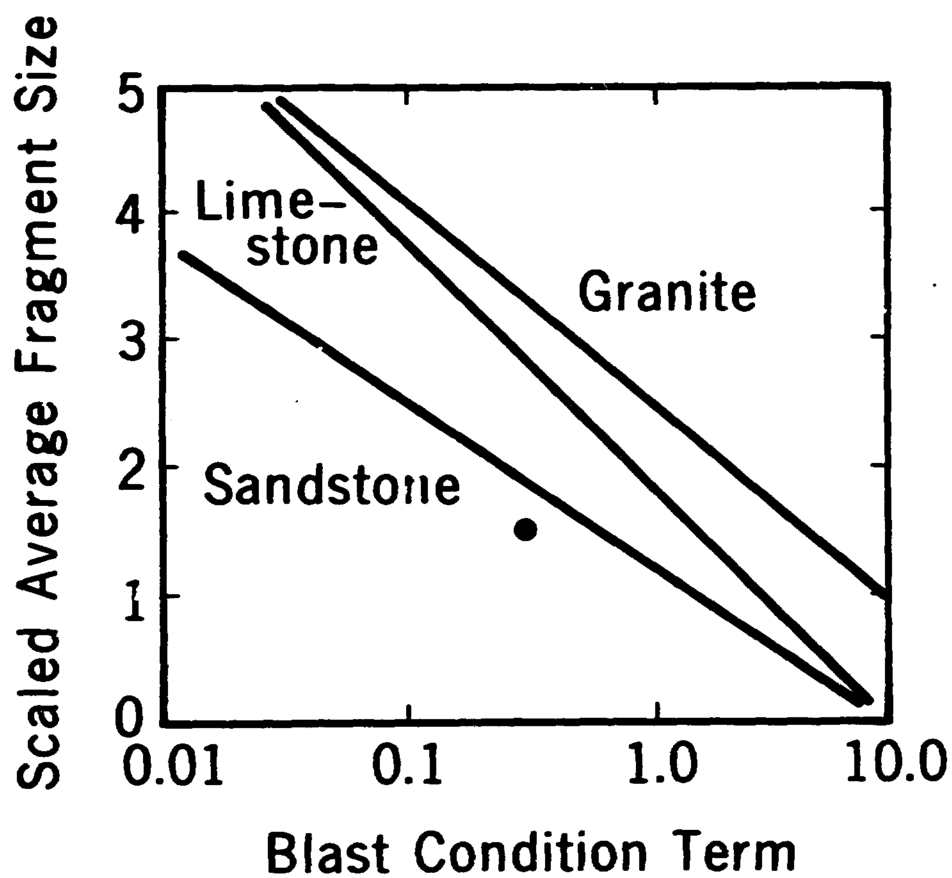

Fig. 6. Fragmentation Scaling Curves. ● – Laboratory bench shot. — – Bergmann, et al.[7] scaling curves.