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TITLE: INSTRUMENTATION AND DIAGNOSTIC TECHNIQUES USED BY LOS ALAMOS NATIONAL LABORATORY IN FRAGMENTATION EXPERIMENTS IN OIL SHALE

AUTHOR(S): C. L. Edwards, G-2
T. F. Adams, G-6
R. D. Dick, G-2

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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INSTRUMENTATION AND DIAGNOSTIC TECHNIQUES USED BY LOS ALAMOS NATIONAL LABORATORY IN FRAGMENTATION EXPERIMENTS IN OIL SHALE

C. L. Edwards
T. F. Adams
R. D. Dick

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

Discussed are the instrumentation and diagnostic techniques used to evaluate the explosive fragmentation experiments in oil shale at the Colony and Anvil Points Mines in Colorado. These experiments were conducted to investigate some of the many parameters that control the fragmenting or rubblizing of oil shale in preparation for subsurface retorting. Framing and TV cameras were used to study the size and speed of the ejected shale fragments. Stress and accelerometer gauges provided quantitative data about the explosively induced stress field in the rock. The CORRTEX technique was used to determine the detonation velocity of the explosive and the induced fracture velocity in the oil shale. Postshot measurements included the crater dimensions and rubble size distribution. In addition preshot and postshot geological mapping was done to relate fractures and joints to crater size and shape. These data are used to compare mathematical models that predict rubblization and retort performance.

I. INTRODUCTION

Large deposits of oil shale in the Green River Formation in Colorado, Utah, and Wyoming have the potential of significantly adding to this country's oil supply. (This reserve is estimated to be about two trillion barrels of oil.) Oil shale is a fine-grained sedimentary rock containing the hydrocarbon kerogen. Through retorting, the oil shale yields organic products, including oil. One of the recovery methods considered, and one that minimizes extensive mining and reduces environmental concerns involves subsurface retorting using the rock formation as the retort. This process requires breaking the oil shale into a suitable size that has a uniformly distributed void volume for fluid flow. Explosives have been used to rubblize the retort volume and distribute the broken shale.

To study bed preparation for a retort, intermediate scale explosive experiments were conducted by the Los Alamos National Laboratory in the ARCO/TOSCO Colony Mine at Parachute, Colorado and Anvil Points oil shale mine near Rifle, Colorado. These experiments varied in purpose, design, and results. Along with the purpose of each experiment, many parameters were varied from one experiment to another, such as amount of instrumentation used, number of explosive boreholes, configuration of experiment (rib or floor), size of explosive boreholes, weight of explosive, geology, etc. The experiments were either conducted in the floor or in the rib (mine wall) of the mines and were designed with either a single explosive borehole or four explosive boreholes placed in a square pattern. The explosive used in these experiments was ammonium nitrate/fuel oil (ANFO). The ANFO, which contained 6 wt% fuel oil, had an average bulk density near 0.84 g/cm³. Depending on the packing of the ANFO when emplaced, the density could range from 0.79 to 0.89 g/cm³. The detonators used varied from commercial blasting caps to exploding bridgewires (EBW). Each experiment was designed to blast to a free face with the ANFO detonated from the bottom of the explosive column. Above the ANFO, the borehole was stemmed to the surface with either grout or oil shale fines.

II. INSTRUMENTATION

The kinds of instrumentation used to provide rock fracturing and fragmentation data were divided between dynamic and postshot measurements. The loading conditions (the stress-strain response of the shale to an explosive charge being detonated in the rock mass) from the dynamic measurements can be linked to the size distribution of the shale fragments from postshot data.

Schematics of the single and multiple borehole experiments illustrating typical dimensions are shown in Figs. 1 and 2. Locations of the experiments in the Colony Mine are shown in Fig. 3.

A. Cameras

TV and framing cameras provided a view of fragments as they left the surface. The video systems were very useful for recording for future playback a broad view of the experimental site, documenting features of the test such as the details of booster assembly, gauge installation, and loading the explosive hole, and real time view of the blast. Because of the slow framing rate of the TV camera (60 frames/s), the velocity of a large percentage of the fragments cannot be determined. However, on some of the first field tests, the surface ejecta was photographed using a Mitchell[1] framing camera with a framing rate of 100 frames/s. By using a common reference on each frame, the speeds of large fragments were found to range from 0 to 22 m/s. This speed range agrees well with predictions from computer calculations by Los Alamos. On future experiments we intend to use one or more Dynafax (Model326)[a] framing cameras to determine more precisely the size, trajectory, and speed of the rock fragments. This style camera is a continuous writing, rotary drum, framing camera that has a variable framing rate of 200 to 26,000 frames/s.

B. Stress Gauges

The stress gauges were grouted in separate instrumentation holes to record the stress loading and response of the rock during the event. The locations of the stress gauges relative to the explosive borehole varied from 1.2 to 3.1 m in the axial direction as measured from the bottom of the charge and 0.5 to 3.2 m radially. For the multiple borehole experiments, the range dimensions were 0.5 to 1.1 m and the axial dimension was 0.9 m. Sandia National Laboratories provided the stress gauges and reduced the gauge records to standard stress units. The techniques and problems associated with the use of stress gauges and the interpretation of stress-gauge records have been discussed by Reed and Boade.[3] The gauges used were either single-element lithium niobate or ytterbium gauges. Each gauge element measures a generalized component of the tensor stress field. The directional sensitivity of the gauges is very difficult to calibrate and may, in fact, depend on the nature of the stress field and the environment in which it is used. Reed[4] has presented a comprehensive discussion of the operation of stress gauges and the techniques used to calibrate them. Figure 4 shows a typical stress gauge record and the predicted stress level.

Calculated first-arrival peak stresses obtained with the Los Alamos code have been compared with the peak stresses observed in three highly instrumented field explosive tests in oil shale. The calculations are generally in good agreement with the observations. Those instances in which the calculated peak mean stress and the observed peak stress do not agree can be understood in terms of differences between the design and actual shot configuration or the effect of the complicated directional sensitivity of the gauges.

C. Accelerometer Gauges

Single-component accelerometer gauges designed for high-amplitude shock wave applications were placed in instrumentation holes to record the g-load experienced by the oil shale at the surface and within the rock mass. The gauge locations relative to the explosive borehole varied in range from 0.5 to 5.0 m for the surface instruments. For the embedded gauges the radial dimensions varied from 1.0 to 3.0 m and axial dimensions were 0.5 and 1.0 m above the top of the explosive column. The accelerometer gauges used were Endevco[a] piezoresistive and PCB[a] piezoelectric devices. These gauges were chosen because of their small size and low mass to provide maximum frequency response to follow fast rise time shock waves as well as long duration motion. The 2264A series of Endevco gauges incorporate a piezoresistive material in two arms of a bridge circuit and fixed resistors in the other two arms. The bridge unbalance due to the g-load is the signal source. The PCB 305A series gauges employ the ICP (Integrated Circuit Piezoelectric) concept for instrumentation, that is, a miniature IC (Integrated Circuit) voltage amplifier or impedance converter is mounted in the same package with the piezoelectric element. This results in a very simple two-wire system that has low noise, high frequency response, high voltage output, and eliminates the need for charge or voltage amplifiers. The gauges were mounted in canisters, about the size of a frozen orange juice can, molded from aluminum-loaded plastic potting compound such that the axial (Z), radial (R), and tangential (T) acceleration components were measured.

Figure 5 is an example of a PCB gauge record from a single borehole test and shows the corresponding computer prediction. As noted, the time-of-arrival (TOA) of the shock wave agrees with calculations to 0.05 ms. Even though the measured and calculated peak g-levels differ by a factor of two, the TOA, shape of the recorded signals, and the g-levels indicated the mathematical models calculated the shale response nearly correct.

D. CORRTEX

The CORRTEX (COntinuous Reflectometry for Radius versus Time EXperiments) systems were used to measure the position of a detonation or shock wave as a function of time. The suitcase-size electronics package emits pulses that travel to the end of a coaxial sensing cable, reflect, and then return to the unit. The CORRTEX unit times and digitizes the travel time of these pulses. In use the sensor cable is crushed diminishing its length as the pressure wave advances. Thus, a time-dependent record of the wave position is obtained with centimeter resolution over a wide range of pressures. Pulsing rates are variable over a range of 10 to 90 μs and two thousand data points are collected. The CORRTEX unit is microprocessor controlled and an accompanying LSI 11-02 computer provides quick response for reducing the field test data, including graphics. This technique was used to measure the ANFO detonation velocity in nearly all the field tests. These data were used to determine (1) if the ANFO detonated, (2) the velocity if detonation occurred, and (3) the steady-state detonation parameters. Figure 6 shows an example of processed CORRTEX data from a sensor cable in ANFO in a borehole. The sensing cable in this example was 6.35-mm-diam Superflexible Heliax coaxial cable (Andrews FSJ1-50). This cable was used because of its low pressure crush threshold. From this particular CORRTEX record, the measured ANFO detonation velocity was 3.9 km/s, which indicates the explosive did reach steady-state detonation. Features of the record are an initial fast shortening of the cable from the effects of the explosive booster, a monotonic decrease in length as the detonation front crushes the cable, a change in slope of the curve at the interface between the ANFO and the stemming, and finally, the cable breaks at the borehole collar.

Another application for CORRTEX is to monitor the propagation of fractures as the rock breaks by placing sensor cables in grouted boreholes located 1 or 2 m from the explosive borehole. Figure 7 is an example of a signal in which FSJ1-50 coaxial cable was run continuously from the bottom of a borehole 1 m from the shot hole into and out of a second borehole 2 m from the shot hole. The indications of shortening of the cable suggest fracture propagation speeds near 3 km/s.

E. Crater Inspection

Postshot measurements of the crater provide the link to dynamic measurements and computer calculations. Crater formation was expected on certain experiments and in many cases was actually an integral part of the experiment. On experiments where crater formation was anticipated, preshot surface profiling and preshot geologic mapping were required. Even the absence of a crater did not preclude the importance of postshot profiling. Postshot crater profiling was used to characterize the residual surface displacement, heaving, and spalling. The profiles were usually oriented normal to each other and passed through the center of the experimental site. Elevations were measured from stadia readings taken 0.3 m intervals across the experimental site. During the profiling of the first few experiments, a stationary string or a line-of-sight method using a Brunton transit was employed but these techniques resulted in errors up to 0.3 m. Most of the remaining experiments incorporated a regular survey transit for profiling with an error probably no greater than 0.03 m. These profile measurments were generally adequate to characterize the crater.

Many of the experiments were designed to investigate the application of the existing scaling laws to oil shale. The scaling laws address the problem of comparing the results of the experiments with varying design parameters on a common scale. The parameters used in these initial investigations of the scaling laws are: (1) the depth of burial (DOB) of the explosive; (2) the depth of the resulting crater; (3) the average radius of the resulting crater; and (4) the volume of the crater. The value of these parameters from different experiments can be compared on a common scale by using an appropriate transformation to a set of scaling variables. The scaled variables for (1), (2), and (3) above were obtained by dividing the parameters by the cube root of the weight of the explosive. The scaled variable for the crater volume is obtained by dividing the volume by the weight of the explosive. Two other parameters included in the scaling laws were critical depth and optimal depth. Critical depth is that depth of burial of the charge below which no surface fracturing occurs. The critical depth value from the field tests was about 18 cm/g$^{1/3}$. Optimal depth is that depth of burial of the charge that yields the greatest crater volume and was found to be 8.5 cm/g$^{1/3}$ or about one-half the critical depth. The volumes of the craters were obtained by excavating the rubble from the crater to the point where it was judged that the oil shale was no longer affected by the explosion. Sometimes this was indeed a judgment decision in the field since the test sites contained numerous pre-existing joints and fractures.

Figure 8 shows the crater profile from a particular test. The charge was a column of ANFO 0.15 m diam by 1.8 m long with 1.5 m of stemming material to the collar. The primary purpose of the experiment was to provide data to study the scaling laws and rubble distribution. The site had prominent joints with strikes ranging from east to east-northeast. During excavation of the crater, the thrown and overturned rock were removed and the resulting crater profiled. This profile is shown in Fig. 8. The rubble that was considered fractured by the explosion was excavated and profiled. Because of the relatively shallow depth of burial of the ANFO, the geology had little effect on the general shape of the crater, and the crater dimensions were fairly symmetric. The calculated profile agrees very well with the actual contours. This provides considerable confidence in the mathematical models.

F. Rubble Screening Data

The rubble size and size distribution have a profound effect on oil shale retort performance and efficiency. Consequently, the screening data is important for calculating the effectiveness of *in situ* retorts. Also, the rubble distribution can be related to scaling parameters. The screening operation for most of the experiments was accomplished in two stages. First, the larger fragments were screened by dumping the excavated rubble through three static screens with sizes of 18-in., 12-in., and 8-in. squares. The remaining rubble that passed through the 8-in. screen was then run through a portable screening unit, Cedarapids model M6016, which contained three screen sizes of 6-in., 4-in., and 2-in. squares. The screened rubble was stacked in seven piles with designations: <2 in, 2 to 4 in., 4 to 6 in., 6 to 8 in., 8 to 12 in., 12 to 18 in., and >18 in. The volume of these piles was then determined and recorded, assuming a porosity within the pile of 0.5.

Figure 9 shows the screening data from a cratering experiment in which a four borehole pattern was used. Three zones were excavated and screened. Zone A was the volume of rubble that occurred between the four explosive boreholes and below the top of the charges, while Zone B was the volume of rubble that occurred between the four explosive boreholes and above the top of the charges. The remaining rubble that consisted of flyrock and fragments that occurred along the perimeter of the crater comprises Zone C. The total volume of rubble excavated was 36.6 m^3. Figure 9 also shows the volume of rubble in each size category for each zone. The rubble from Zones A and B appeared to follow an approximate log-linear scale curve. The flyrock, however, can be approximated by a linear curve.

III. SUMMARY

The instrumentation and experimental techniques used in cratering tests in the field include fast and slow framing cameras, video coverage of the event, stress and accelerometer gauges to record rock response over a 20-ms duration, CORRTEX methods to monitor explosive performance such as the measurement of the detonation speed and steady-state behavior, and postshot evaluation such as measuring the crater volumes and profiles, determining geological influences, and screening the rubble to define the rubble size and distribution. These data provide a basis for the mathematical models for computing the response of the oil shale when shock loaded and evaluating the performance and efficiency of a commercial size *in situ* retort.

REFERENCES

1. Mitchell, trade name.

2. Dynafax, trade name.

3. Reed, R.P. and R.R. Boade, "Techniques and Problems Relating to In Situ Measurement of Stress Waves in Rubblization Experiments," Proc. of the 20th U.S. Symposium on Rock Mechanics, Austin, Texas, June 4-6, 1979.

4. Reed, R.P., "Triaxial Measurement of Stress Waves in the Free Field," Range Commander's Council, Tenth Transducer Workshop, Colorado, Springs, Colorado, June 12-14, 1979.

5. Endevoco is a registered trade name for the company that manufactures piezoresistive accelerometer gauges.

6. PCB is the name of the company that manufactures the piezoelectric accelerometers.

7. Virchow, C.F., G.E. Conrad, and D.M. Holt, "Microprocessor-Controlled Time Domain Reflectometer for Dynamic Shock Position Measurements," Rev. Sci. Instrum. 51, 642 (1980).

8. Harper, M.D. and R. Oliver, "Data from the Screening of the Rubble from Eight Cratering Experiments in Oil Shale," Los Alamos National Laboratory Report LA-8732-MS, March 1981.

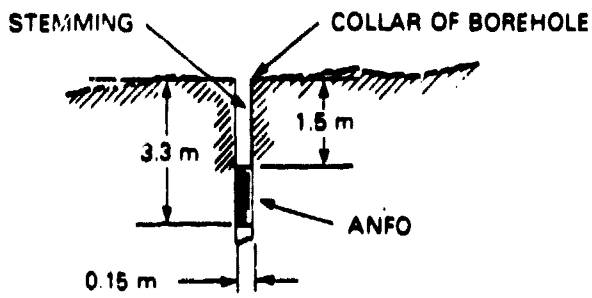


Fig. 1. Schematic of the single-borehole tests.

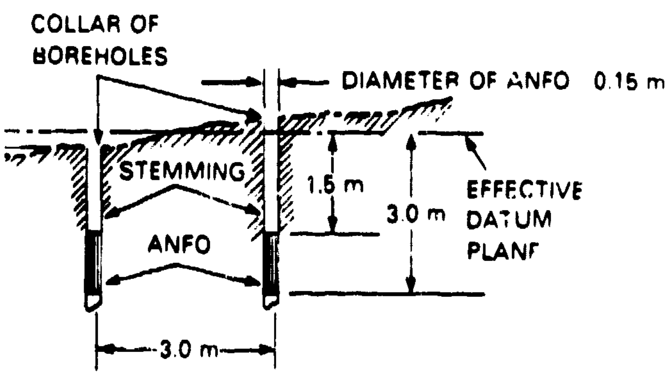


Fig. 2. Schematic of the multiple-borehole tests.

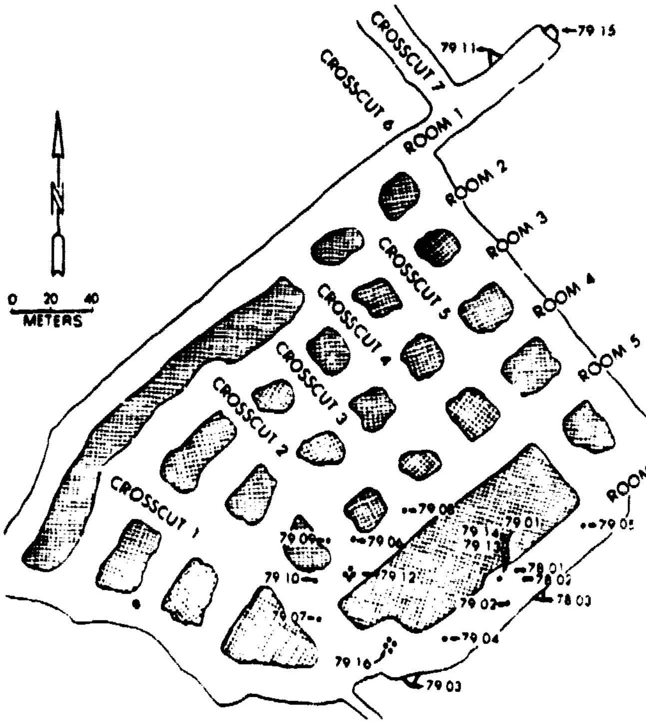


Fig. 3. Map of the Colony Mine and the location of the tests.

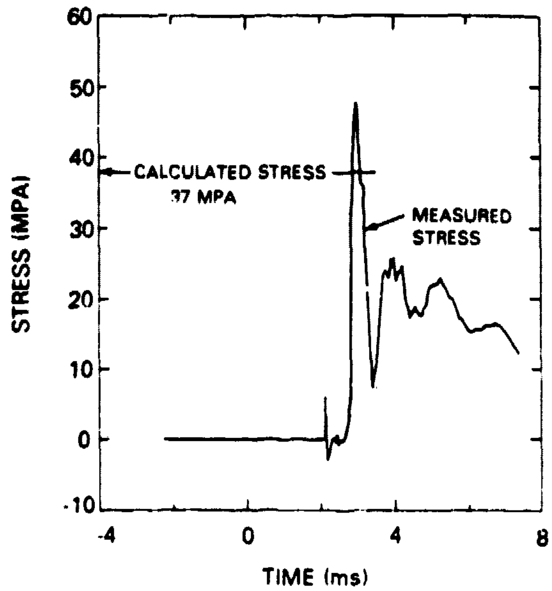


Fig. 4. Typical stress gauge record, including the predicted stress level.

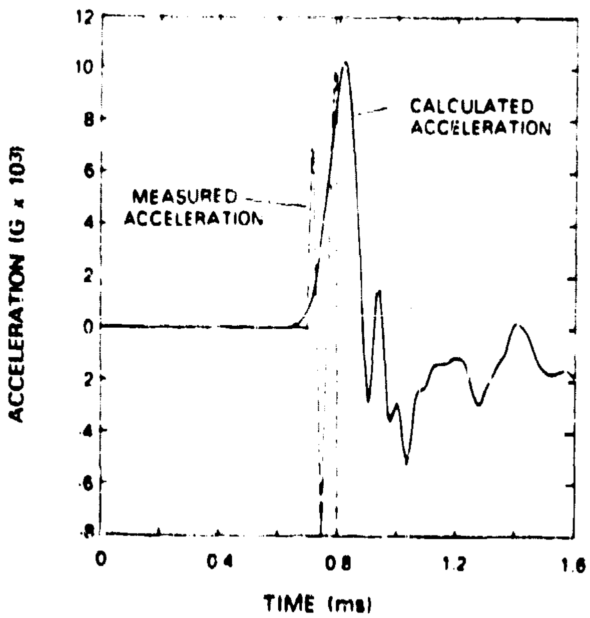


Fig. 5. Example of the PCB accelerometer gauge record with the corresponding predicted acceleration.

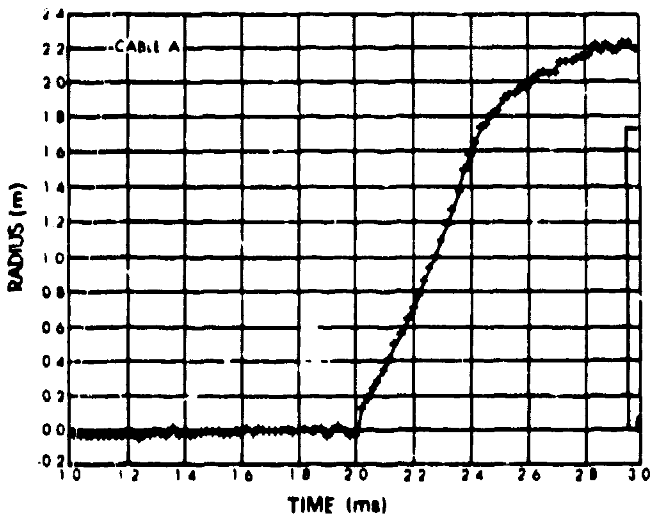


Fig. 6. Example of processed CORRTEX data from a sensor cable in ANFO.

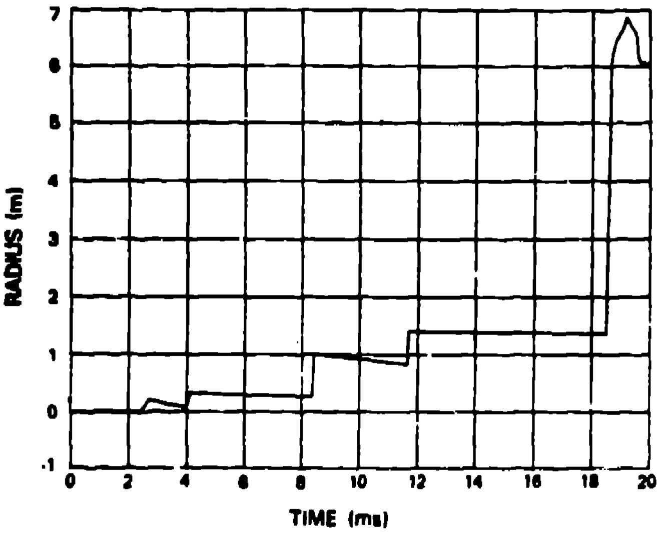


Fig. 7. CORRTEX record from a sensor cable in a borehole one meter from the shot hole.

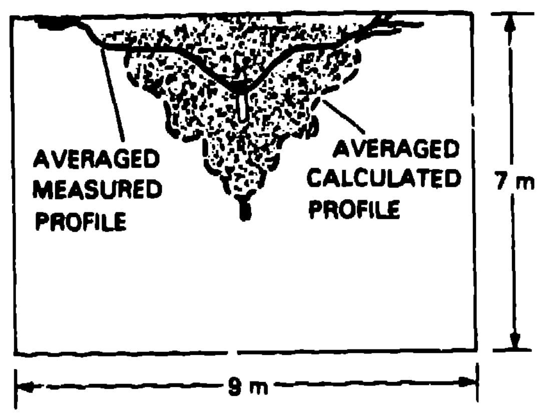
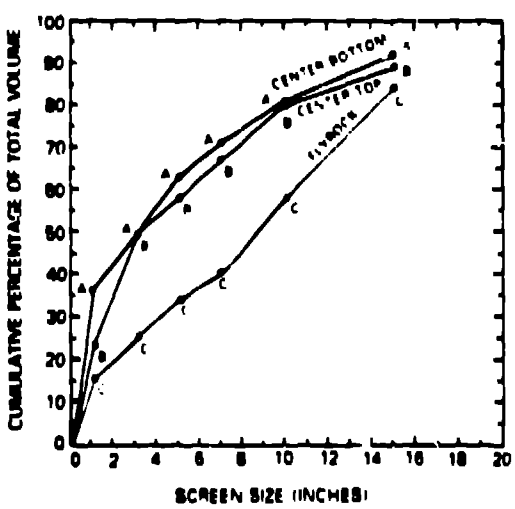


Fig. 8. Comparison of a measured crater profile with predictions.



SCREEN SIZE (in.)	VOLUME OF ROCK (m^3) ZONE A	ZONE B	ZONE C
<2	2.6	1.1	3.6
2 to 4	0.9	1.2	2.4
4 to 6	1.0	0.4	2.1
6 to 8	0.6	0.4	1.4
8 to 12	0.7	0.6	4.4
12 to 18	0.8	0.4	6.4
>18	0.6	0.6	4.4
TOTAL	7.2	4.7	24.7

Fig. 9. Rubble screening data from a four borehole test.