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TITLE MODELING OF BURIED EXPLOSIONS

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MODELING OF BURIED EXPLOSIONS

by

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Los Alamos National Laboratory has been and continues developing techniques for modeling buried explosions using a large geotechnical centrifuge. When fully developed, the techniques should permit the accurate modeling of large explosions in complex geometries. Our internal application is to study the phenomena of explosive cavity formation and collapse. However, the same methods should also be applicable to simulation of bursts shallow enough to produce craters, and perhaps even of airbursts in situations where soil overburden is important. We have placed primary emphasis on test bed construction methods and on accurate measurement of the ground shock produced by the explosions.

## I. INTRODUCTION

The underground nuclear test community has long been interested in the formation and collapse of explosion cavities and other post-event phenomena. These are directly applicable to designs for the containment of radioactivity for future underground nuclear tests as well as problems related to new test holes in proximity to previous tests, the latter being a function of conservation of real estate at the Department of Energy's Nevada Test Site where all U.S. underground nuclear testing is conducted. In this regard we have initiated a program at the Los Alamos National Laboratory to model these effectc using scaled explosions in media similar to that encountered in NTS emplacement holes. Previous work (1, 2 & 3) has verified the efficacy of scale model testing as related to underground nuclear testing.

Scale modeling of explosions to simulate the attack of conventional munitions on military and civilian structures presents the possibility of obtaining necessary information about survivability and vulnerability at substantially reduced cost. However, since both strength and modulus of soils depends on confining stress, proper similitude in subscale tests is often not possible without using extreme modifications to the test media or conducting the test at high g on a centrifuge. One of the goals of this effort is to develop techniques for measuring the free-field effects of explosions meant to simulate large conventional munitions. For example, using the general centrifuge scaling

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relations (4), we would use a 4 gram charge in a test at 50 g's to simulate the explosion of a 500 kg burst at 1 g. The cost of model construction and testing on a centrifuge is very small by comparison with that of a full scale test. Because of the small cost, more tests can be done, and testing can more accurately determine the limits of failure.

The effort currently in progress at Los Alamos is focused on both gauge and test bed development. The goal of the program is to develop reliable testing techniques for use in scaled explosive events carried out on a centrifuge.

## II. TEST DESCRIPTION

A test bed consisting of washed sand provides a simple setup for testing stress gauges and accelerometers in a spherical geometry. With this material simple placement of an explosive charge and a gauge array in a specified horizon facilitates measurement of a spherically diverging stress wave in a soil-like medium as well as post-shot inspection of the shot horizon and gauge condition. This experimental setup was chosen especially for its ease in construction.

Spherical explosive charges of C-4 were 38 mm in diameter (approximately 46 g) and initiated by Reynolds RP-87 detonators; the stress wave reached the sand at about 5.4 microseconds after detonation. Detonator leads were run out of the test bed on the opposite side of where the gauge array was placed.

Gauge arrays were set up to measure stress and accelerations at two radial distances, typically from 50 to 200 mm on a horizontal plane. A photograph of one array at shot level is shown in figure 1. Although much care was taken to achieve specific gauge location and orientation, subsequent gauge movement probably occurred during backfill of the test bed.

The test bed consisted of two levels separated by a shot level template with a 1.5 m diameter test horizon. The upper level was emplaced after charge and gauge layout, and the template provided a means for locating the post shot excavation. Burial depths range from 600 to 700 mm. A photograph of the test bed is shown in figure 2. The washed sand used ranged in approximate grain diameters (one standard deviation) from about one-half millimeter to several millimeters with infrequent large grains up to several centimeters. Sand, sieved through 2 mm screens, was carefully placed around gauges and the charge to insure as much homogeneity as possible. Wet sand density was typically 1.6 to 1.7 $Mg/m^3$ at 5 weight percent saturation. However, heterogeneity was difficult to overcome in construction of the test bed.

## III. MEASUREMENTS

The measurement of ground shock from small explosions has been accomplished numerous times. SRI International has reported an extensive program of measurements in grout (intended to simulate volcanic tuff) and reconstituted alluvium (5). Most of their measurements were of the lagrangian radial velocity, although they did make some measurements of the radial stress. The velocity measurements were made by monitoring the current induced in a circular coil concentric about the charge as it moved outward while cutting lines of flux in a uniform magnetic field. This has proven to be a very reliable technique; unfortunately, it would be impossible to implement on a centrifuge test because the uniform field is produced by a pair of large Helmholtz coils. The mass of these coils is too great for incorporation in a centrifuge test. In addition, the power required would be beyond the limits which could be delivered to the centrifuge arm.

### A. Gauges

#### 1. Manganin Stress Gauges

Our Manganin gauge design was previously described (6); it is a probe-like package in which the gauge element is mounted on a polycarbonate support such that the gauge leads are at right angles to the sensitive element. This arrangement, along with a coaxial shorting pin (for triggering recording devices), is potted in epoxy to insure mechanical stability. The epoxy may be treated to obtain reasonable impedance matching with the test bed. However, the radial probe nature of this gauge package does not promote lagrangian measurements, especially in semi-compressible media such as our sand test beds. Results obtained include dynamic and reflected stress components that must be unfolded in order to obtain free-field stress. Still, the package appears to be rugged and capable of surviving stress waves of several tens of MPa in the sand test beds. The coaxial trigger pin is not required with the digital recording system but is ultimately necessary for adequate oscilloscope records.

#### 2. Carbon piezoresistive stress gauges.

Carbon piezoresistive film stress gauges have been used in a flat-pack configuration to measure radial stress-time histories at medium ranges, corresponding to pressures of tens to hundreds of MPa. As commercially supplied*, the 50 piezoresistive film and foil leads are encapsulated between

*Dynasen, Inc., Goleta, CA, USA

thin (.025 mm) layers of kapton. For greater survivability, we have added a layer of .25 mm thick mica to each side of the gauge, and gradually increased the flat-pack thickness from 0.55 mm at the gauge sensing element (7.6 mm x 12.7 mm), to 6.5 mm at the end of the gauge where the coaxial cable lead (RG-174) exits, by filling between the mica strips with fast-setting epoxy. The final gauge package is thus a wedge shape of 115 mm x 25 mm cross section. This arrangement maximizes the chances of gauge survival while preserving the lagrangian response of the gauge and mimimizing the inclusion effect at the sensing element.

Carbon gauges of this type are valuable for their high sensitivity in the low stress (<1 GPa) regime, and because their sensing elements form a single wide strip rather than a conducting grid, they are less susceptible to destruction through puncture by individual material grains. The response of these gauge packages in the current test configuration will be described below.

3. Other

Preliminary measurements of acceleration are made using a micro-miniature shock accelerometer. Endevco model 2291* is a piezoelectric transducer capable of withstanding 100,000 g in any direction. Its small mass (1.3 grams) and high resonance frequency (250 kHz) make it adequate for acceleration measurements at ranges of greater than 100 to 200 mm where stresses have decayed to under 100 MPa and stress rise times are nearly 100 microseconds long. Still, higher frequency records are desired, and since particle velocity records are the required data, we do not anticipate further development of acceleration measurements, since data integration is required to get velocities. These accelerometers are mounted on one inch squares of quarter-inch thick polycarbonate in order to facilitated orientation of the gauge. This mounting may prove to be inadequate for good coupling with test bed materials.

Because of the difficulty of implementing other particle velocity measurement techniques on a centrifuge, we have attempted to adapt a technique from field methods. The mutual inductance particle velocity (MIPV) gauge (7) consists of two nearly coincident coils in the shape of a long, thin rectangle whose long axis lies on a radius from the charge. A constant current of several tens of amperes flowing through one coil links flux through the other. As the coils are deformed the mutual inductance is changed, which produces a

*Endevco, San Juan Capistrano, CA, USA.

current in the other coil which is proportional to the velocity of the end of the coils nearest the charge. At the time of this writing we have constructed such a gauge with the necessary power supply. It will be used to measure free-field particle velocity from a contained burst in January 1987.

B. Data Acquisition

For this study, we have constructed a multi-channel digital data acquisition system which was designed to be reasonably portable for transport to and use at remote facilities. The system is computer controlled, utilizing the CAMAC (IEEE-583) interface standard.

Signals from the carbon and manganin piezoresistive stress gauges are obtained from pulsed-d.c. Wheatstone bridge power supplies*, which are typically triggered for a duration of 500 microseconds, resulting in less than 5 percent decay of the voltage applied to the gauges. We use excitation voltages of 70v and 200v for the carbon and manganin gauges, respectively, representing an optimum balance between gauge sensitivity and joule heating effects in the gauge packages. The dual-channel power supplies can be triggered independently, resulting in flexibility in the timing of the gauge activation with respect to arrival of the stress wave wave at the various gauge positions. Voltage records from the accelerometers are obtained from charge amplifers, and other types of gauges supplying voltage or current signals can be accommodated.

The data recording system resides in two CAMAC crates and consists of multi-channel timing delays units, trigger generators, amplifier/alternators, and transient waveform digitizers with associated memory modules. The nine waveform digitizers are of two types (LeCroy 2264/8800 and 8818/8105)**, which together allow recording of signals at rates from 1 MHz to 100 MHz, for up to 14 channels of data, and durations of several milliseconds per channel. The recorders are controlled and the data acquired by a minicomputer (DEC LSI 11/23)*** through the two crate controllers (Kinetic Systems 3912-Z1G)****. The timing delay system, with the detonator trigger as a source, supplies appropriately timed trigger signals for the bridge power supplies and the waveform recorders, in order to position the stress wave within the bridge excitation time, and the latter within the duration of the recording "windows."

*Dynasen, Inc., Goleta, CA, USA
**LeCroy Research Systems Corp., Spring Valley, NY, USA
***Digital Equipment Corp., Maynard, MA, USA
****Kinetic Systems Corp., Lockport, IL, USA

Following data collection, the computer reads the contents of memory for each data channel sequentially, storing the information in files of binary format on flexible disk and/or magnetic tape cartridge. These media can then be transported to a large computer for later display and analysis.

### C. Post-test Measurements

Post shot measurements consist of two data sets. The first is accurate measurement of the test bed deformation such as collapse pit dimensions, fracture geometry, and compaction. The second requires excavation back to the shot level without disturbing gauges and detonation products. After excavation a reasonable measure of transient cavity dimensions is made by noting location of detonation products. The final location and integrity of gauge packages is important for interpreting gauge records and also as a valuable aid in gauge development, so type of gauge destruction and movement are noted.

## IV. RESULTS

An important goal of this study is to investigate the suitability of various techniques for measuring free-field stresses during small-scale explosive tests carried out on a centrifuge. The gauges should be sensitive enough to measure stresses at ranges of several cavity radii in highly attenuating media such as dry desert alluvium, but rugged enough to survive the strong spherical flow environment at closer ranges. Also, aspects of gauge response in spherical flow, such as strain sensitivity and transverse stress response, must be understood and characterized. In this section we show some early records obtained from carbon and manganin stress gauges, and give a preliminary qualitative discussion of some of their features.

Another important aspect of this work is the analysis of the post-shot condition of the test bed. Below we describe this post-test inspection process for a typical experiment in unsaturated wet sand.

### A. Gauge Records

Figures 3 and 4 are records obtained from carbon gauges in two separate tests. In both tests, the charge consisted of approximately 45 grams of high explosive contained in a hollow plastic sphere approximately 3 cm in diameter and center-initiated. The carbon gauge packages were oriented to measure radial stress at ranges of 50 and 120 mm, respectively. The horizontal scale in the figures refers to elapsed time since charge initiation. The negative-going signals represent the decrease in the piezoresistivity of the carbon film elements with increasing compressive stress. In figure 3 the large noise spikes at about 10 microseconds are a result of the detonator signal.

Similar qualitative features can be observed in figures 3 and 4. In both cases, gauge failure is preceeded by recording a roughly triangular stress pulse, with some oscillatory behavior seen in both traces. The risetime of the signal is considerably longer (and the stress recorded considerably lower) in the more distant gauge, however the failure for this gauge is apparently more precipitous, which may have affected the peak stress recorded. The high piezoresistivity of the carbon gauges leads one to expect a relatively lower strain response (8), however this is a possible explanation for the positive-going precursor observed in figure 4, where the total change in resistance is only 0.2 percent. The oscillatory behavior mentioned above can be tentatively attributed to the overall mechanical response of the gauge package to non-planar flow, which is not yet well understood.

Figure 5 shows the response of a manganin gauge to a similar test, at a range of 200 mm. Because of the higher-than-anticipated stress, the signal's peak exceeds the preset range of the recording system. However, several features remain to be interpreted.

As before, one can see the induced noise shortly following detonation. The large transient signal at approximately 100 microseconds is the beginning of the power supply current pulse, followed by some "settling" behavior that seems to result from significant deviations from 50 $\Omega$ in the initial gauge resistance, which in this case was about 45 $\Omega$. Then follows a slow decrease in baseline, showing a decrease in resistance of the gauge as it heats up. Neither this record, nor the two carbon gauge traces described above, are corrected for this joule heating effect. In practice, we obtain a baseline gauge record for each gauge after building the test bed but before firing, to be subtracted later from the recorded data.

The design of the manganin gauge package precludes a lagrangian response to the flow, and the impedance mismatch to the surrounding medium is such that one expects the recorded stress to be approximately twice that of the free field. The positive-going signal reflects the increase of manganin's piezoresistivity with increasing compressive stress. The risetime of the stress signal is consistant with that measured with carbon gauges, given the greater range of the manganin gauge. The extended duration is presumably an effect of the massive gauge package and its radial orientation. This gauge did not fail during the test and survived intact.

From these early results, some preliminary conclusions regarding gauges and gauge package design can be made. Because of their thinness in the direction of flow, the carbon gauges should accurately measure the free-field stress in lagrangian coordinates. However, this property is a detriment to survivability. The manganin gauges, packaged much more massively, measure an interface stress which is much higher than the free-field stress. However, this effect can presumably be accounted for. Finally, further work is required to understand the response of the gauge packages (not just the sensing element materials) to spherically diverging flow, with regard to both stress and strain sensitivity.

B. Post-shot Test Bed Analysis

Post-shot examination of the test bed shows formation of a collapse crater, radial and concentric fractures extending away from and around the crater, and inward dipping slump faults on the crater's inside slopes. Figure 6 is a photograph of post-shot, test-bed deformation. A typical collapse crater may range from 30 to 50 cm in diamter and 10 to 15 cm deep. Major concentric fractures are spaced from 5 to 15 cm apart, while radial fractures are oriented at 20 to 40 degree intervals. The whole test-bed surface may show several centimeters of subsidence. Although we have not obtained time records of collapse phenomena, direct observations indicate that the test bed deformation occurs within one second after detonation.

Excavation of the test bed reveals that gauges have been displaced and damaged, especially those located within 100 mm of the charge. This observation is not surprising because existence of detonation products up to 200 mm from ground zero suggests considerable growth of a transient explosion cavity. As shown in figure 7, detonation products are typically found within a radius 150 mm. We believe that this value is a characteristic measure of the transient cavity radius, becuase the relatively massive gauge packages placed within this region have been displaced outward to the observed limit of detonation products, and the cavity volume corresponding to this radius is approximately that of the collapse crater (i.e. the cavity has been filled in primarily by collapse of roof materials).

As noted above, all the gauges are displaced during propagation of the strain wave produced by the detonation. Least affected are the probe-like manganin packages and greatest displacement is noted for the carbon flat packs. Accelerometers show up to several cm of radial displacement as well as rotation. Typically, the carbon flat packs show damage dependent upon their initial position. Gauges placed normal to radial stresses show one or several breaks transverse to the long axis, while gauges placed to measure hoop stress split along the long axis where the gauge is bonded to the mica backing. When damaged, manganin gauges are broken transverse to their long axes and along interfaces between the gauge support and surrounding epoxy. However, we note that both carbon and manganin gauge packages are reuseable when they have been placed at ranges near 200 mm. In fact one manganin gauge has survived two shots while providing good stress records on both. Finally, no damage has been noted on accelerometers, although it is likely that the polycarbonate gauge mount has prevented good acceleration measurements.

## IV. SUMMARY

An interest in the processes of cavity formation and collapse resulting from contained nuclear explosions, as well as modeling of crater formation from buried conventional munitions, has led us to initiate a program at Los Alamos National Laboratory to model these effects using small-scale high-explosive tests. We are concentrating thus far on gauge construction and performance, and on techniques for test-bed construction and post-test evaluation.

The very difficult problem of construction of test beds in media such as unsaturated wet alluvium, is also being investigated. Uniform and well characterized density, accurate gauge emplacement, and test bed characteristics required to produce burst containment, cavity collapse, and crater formation are being studied. Also, techniques for accurate post-test analysis of these effects are of concern, as well as examination of final gauge condition as an aid in design of survivable gauge packages.

Gauges under study include: carbon and manganin piezoresistive stress gauges; small, high-frequency accelerometers; and a new type of mutual inductance particle velocity gauge. The response of these gauges in spherically diverging flow is of primary interest.

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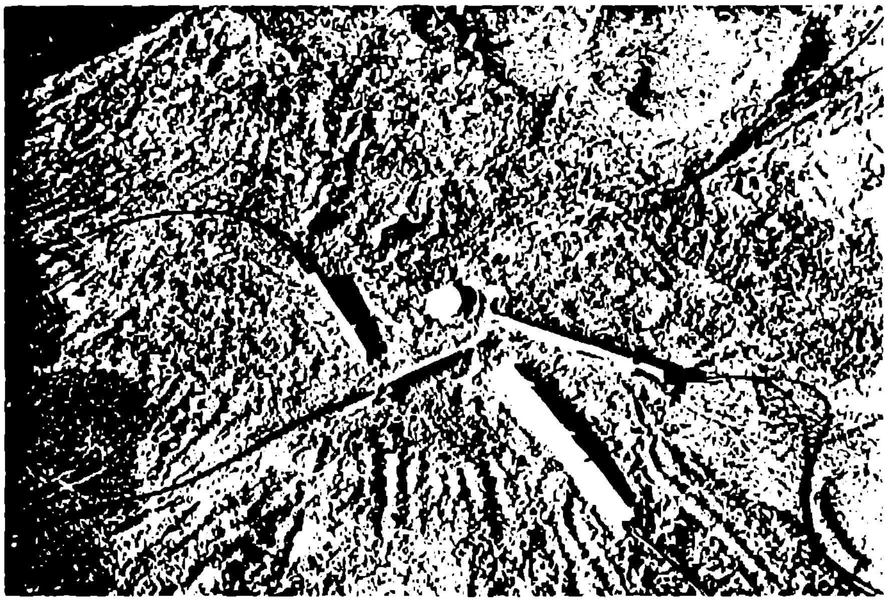

Figure 1. Photograph of the gauge array used in shot 86-2. The test bed is shown at shot level with spherical C-4 charge in center, carbon gauges (wedge shaped), manganin gauge (cylindrical), and accelerometers (small blocks), oriented around the charge. The total diameter of controlled space in the test bed is about 1.5 meters.

Figure 2. Photograph of the test bed after it has been back-filled over shot layer. The back fill is such that its depth above the charge is sufficient to allow formation of a collapse crater, and its surface diameter is several times larger than that of the expected collapse crater.

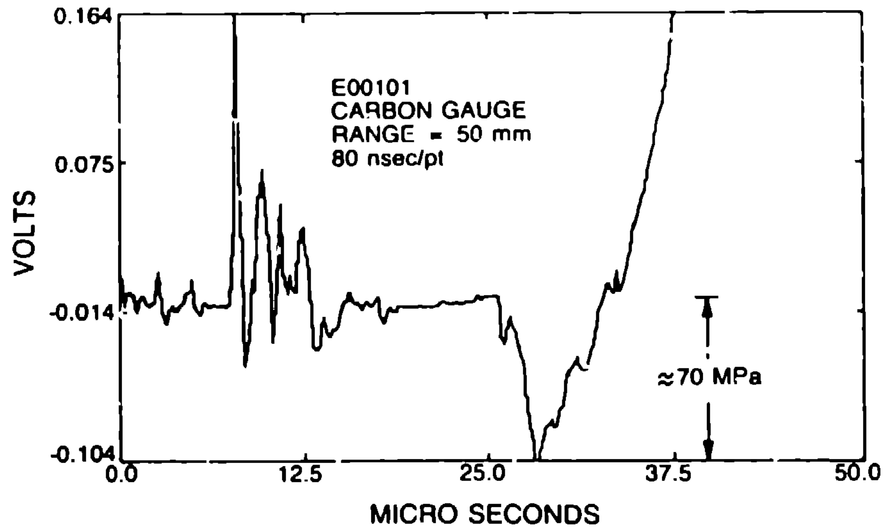


Figure 3. Plot of carbon gauge response versus time. Note that the stress wave arrives at about 25 microseconds after detonation and produces a negative gauge response. Shearing of the gauge electrical leads causes the record to move off scale in a positive direction.

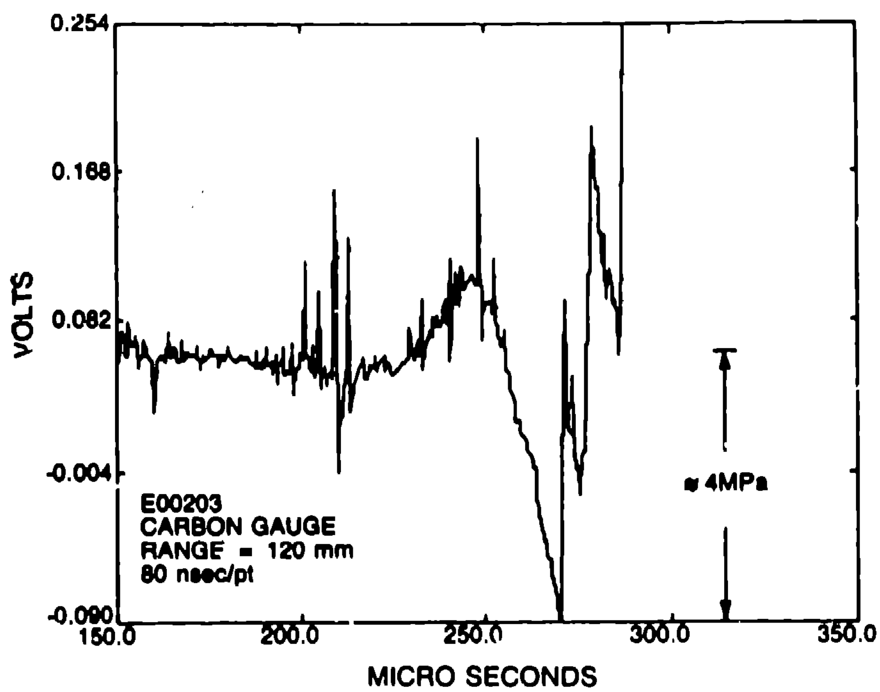


Figure 4. Plot of carbon gauge response versus time. The stress wave arrives at about 250 microseconds after detonation and demonstrates a trace complicated by the possible positive response of the gauge to lateral strain associated with the spherically diverging stress wave.

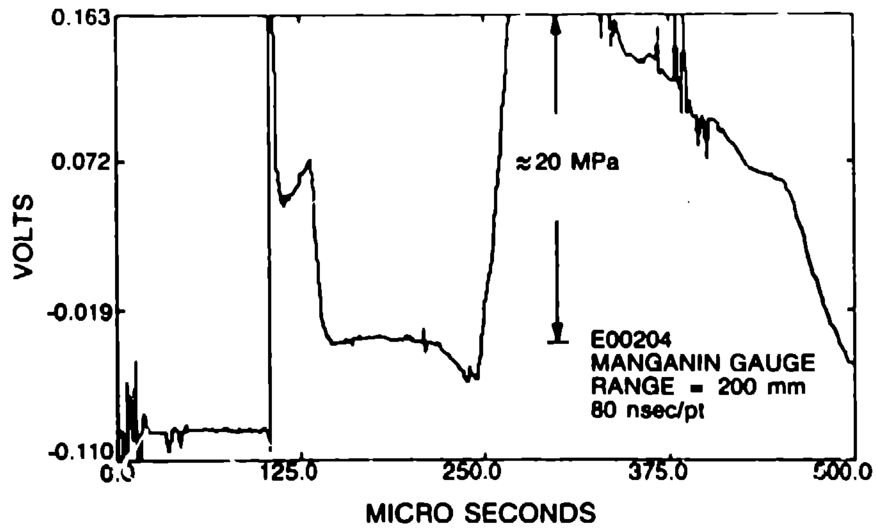


Figure 5. Plot of manganin gauge response versus time. Note that the stress wave produces a positive response that exceeded the recording limit, and that the power supply turn-on characteristic at 100 microseconds lasts for over 20 microseconds.

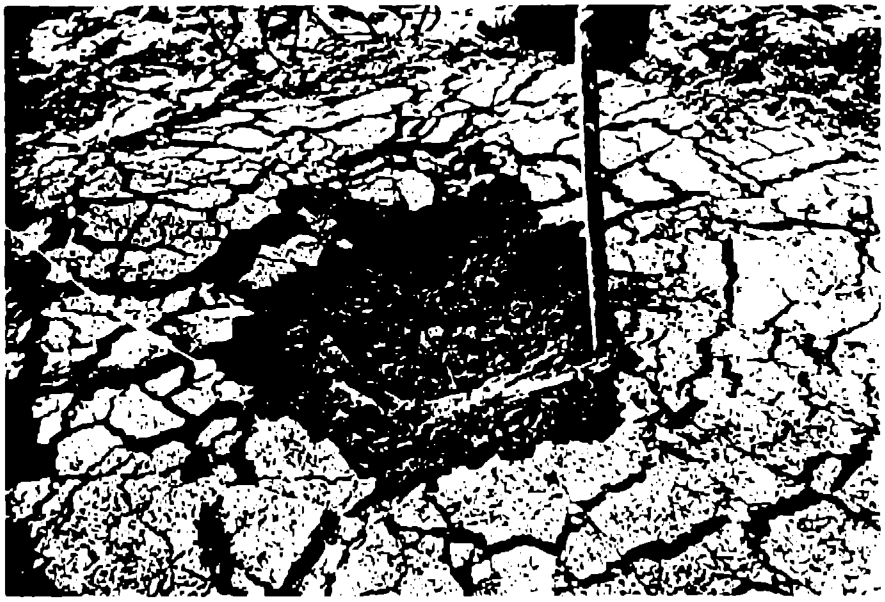

Figure 6. Photograph showing test-bed deformation: a collapse crater nearly 50 cm in diameter and 15 cm in depth and uniformly spaced concentric and radial fractures surrounding the collapse crater.

Figure 7. Photograph of the post-shot excavation (86-2). The string outlines the maximum limit of observed detonation products (white and dark gray shades). Numbers refer to: (1) carbon gauge package with an initial tangential orientation at 70 mm, (2) carbon gauge package with an initial radial orientation at 70 mm, (3) carbon gauge package initially at 120 mm, (4) manganin gauge initially at 120 mm, (5) accelerometer initially at 120 mm, and (6) accelerometer initially at 200 mm. Gauge displacements and damage are readily apparent in this picture as is an approximate radius of the transient cavity.