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SIMULATION OF STRONG EARTHQUAKE MOTION WITH EXPLOSIVE LINE SOURCE ARRAYS

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ABSTRACT

The need for an in-situ test technique to guide the design of earthquake-resistant structures has long been recognized. Over the past year SRI International has been conducting an investigation funded by National Science Foundation Grant ENV76-23273 on the feasibility of simulating earthquakes by contained explosions in line source arrays. The technique consists of detonating a plane array of vertical line sources placed in the vicinity of the structure to be tested. In a full-scale test the array might measure 100 x 30 ft, consist of 10 to 20 vertical bore holes 30-ft deep spaced on 5- to 10-ft centers, placed about 30 ft from the structure to be tested.

During the first year, reusable hardware was developed for producing contained explosions in a 1/3-scale source, instrumentation was incorporated for hardware diagnostics and output measurements, reasonable acceleration and frequencies were obtained in soil with the 1/3-scale source, and repeatable results were demonstrated.

Estimates based on our current experiments show that in a 100- x 30-ft array, a 5-Hz pulse with a 0.5-g peak acceleration can be produced with less than 100 lb of explosive. A complete train of oscillations typical of strong earthquake motion with a total duration of 10 s and peak accelerations reaching 1 g, is estimated to require about 500 lb of explosive, fired in 10 detonations.

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PREFACE

This report describes an experimental investigation of the feasibility of simulating strong earthquake motion with contained explosive line source arrays. The investigation was divided into four parts: (1) design of a 1/3-scale line source, (2) testing the 1/3-scale line source in a sand pit, (3) testing the 1/3-scale line source in the soil, and (4) analysis to predict ground motion for an array of line sources.

This research program was supported by the National Science Foundation under Grant No. ENV76-23273. Dr. Michael Gaus, National Science Foundation, was the program manager.

Kenneth Mock fabricated the parts for the line source. Hugh Hanna and Curtis Benson assembled the line source and assisted in carrying out the experiments. William Heckman performed the electronic measurements. Betty Bain and Ceryl Stout reduced the data. Dr. Leonard Schwer assisted on the numerical computation of ground response for a single source and an array of sources.

I INTRODUCTION AND SUMMARY

A. Background

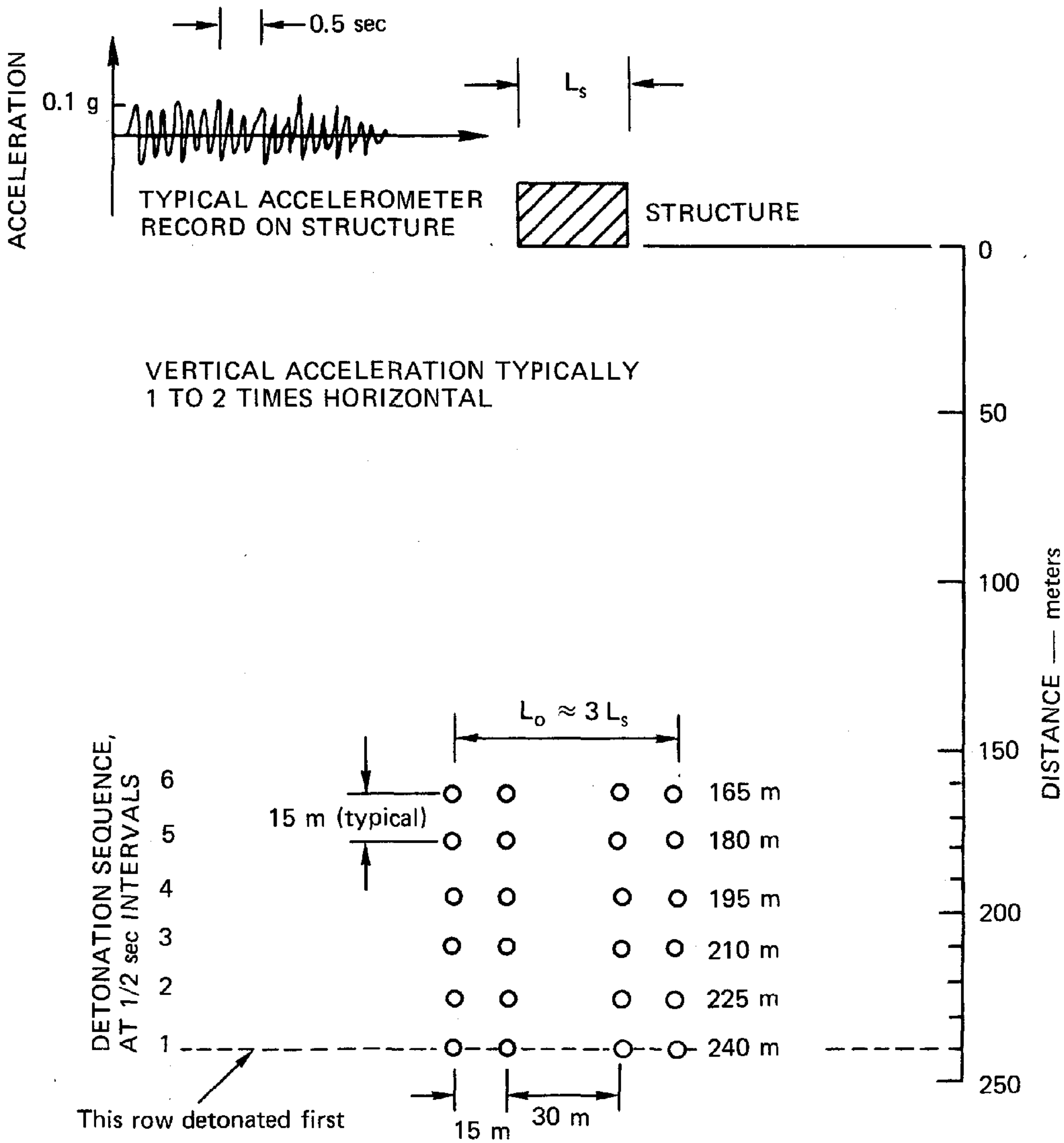
The need for an in-situ test technique to guide the design of earthquake-resistant structures has long been recognized. This need has become more acute with the development of nuclear reactors, greater population concentrations, and the more efficient structural designs that are made possible by computer technology.

High explosives have been used for the in-situ testing of both full-scale and small-scale structures. C. B. Smith and R. B. Matthiesen, formerly professors at UCLA, undertook an extensive program of in-situ testing at available sites during the summers of the late 1960s and early 1970s. In four of their test programs,[1] vibration motion was produced with point charges of explosive. Borehole depths ranged from about 10 to 60 ft, charged weights ranged from a few to 2000 lb, and the distance from full-scale structures ranged from 250 to 900 ft. These four explosive test programs took place at the Fermi plant near Detroit, Michigan, in 1969; at the Experimental Gas-Cooled Reactor at Oak Ridge, Tennessee, in 1970; at the UCLA Field Station at Oak Ridge Canyon, California, in 1971 (scale models); and at the Old Bailey substation of the Southern California Edison Company near Gorman, California, in 1972. Although these tests successfully demonstrated the application of explosives to the observation of reactor vibrations, including soil-structure interaction, they were conducted mainly at small amplitudes to observe linear vibration modes.

An explosive technique for seismic testing of in-situ structures at large amplitudes has been developed at the Tadzhikistan Institute of Seismic Research (USSR).[2] The technique was developed to simulate complete earthquakes and to produce representative response and damage in full-scale structures. Explosive charges of 1 to 20 ton are buried in spherical cavities at the base of holes 30-m deep, and simulated earthquakes lasting 5 s are produced by sequentially detonating rows of charges (Figure 1). Because this technique produces extensive cratering and soil is thrown hundreds of feet into the air, it is used only at a remote testing site.

The Electric Power Research Institute (EPRI) funded a program with the University of New Mexico's Civil Engineering Research Facility (CERF) for in-situ testing of small-scale reactor containment structures.[3] The principal objective of the program was to study soil-structure interaction during strong ground motion. Ground motion was generated by using two arrays of explosive line charges. The arrays consisted of holes 100-ft deep, with the lower 75 ft filled with explosive and the top 25 ft capped with sandstone. The array closest to the structures contained 30 ton of explosive distributed in 16 holes and was approximately 150 ft from the structures. The other array was 70 ft farther from the structures, and contained 40 ton of explosive distributed in 12 holes. Five structures from 1/48 to 1/12 scale and from 1/4 to fully buried were tested. Again, there was extensive cratering and soil was thrown into the air so that testing was necessarily performed at a remote site.

Over the past year, SRI International has been conducting an investigation funded by the National Science Foundation on the feasibility of simulating earthquakes by contained explosions in line source arrays. This investigation was based on our experinece over the past 15 years with similar arrays for simulating airblasts, underwater blasts, and internal blasts from postulated nuclear reactor loss-of-coolant accidents. We believe that contained explosions are more advantageous for seismic testing of structures than freely expanding explosions because they produce lower pressures and hence local ground motions in the range of interest for structural testing. Therefore, they can be used closer to test structures, require smaller amounts of explosive, and produce no surface eruptions. Because the contained line sources are not damaged during the test, they can be used a number of times for repeat or parameter testing at the same location within a relatively short time.



O 24 HALF-TON CHARGES AT BASE OF 30 m DRILL HOLES
(Total charge 12 tons)

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FIGURE 1 TEST CONFIGURATION AT THE TADZHIKISTAN INSTITUTE OF SEISMIC RESEARCH (USSR)

B. Simulation Technique

The simulation technique consists of detonating a plane array of vertical line sources placed in the soil near the structure to be tested. Each line source produces ground motion through an expandable rubber bladder rugged enough to withstand repeated tests that produce expansions to roughly twice the initial bladder diameter. The explosive is detonated inside a steel canister within the bladder and the explosion products flow out of the canister through vent holes to pressurize the bladder at a controlled rate. Pressure pulse rise times are controlled by the size of the vent holes in the canister, and decay times can be controlled by venting the bladder to the atmosphere.

The key features of the line sources are (1) a minimum amount of explosive is required because containing the explosion products eliminates the high ground shocks associated with freely expanding explosions, and therefore the line source array can be located close to the structure; (2) the line sources are reusable and give repeatable results; (3) the duration of the simulated earthquake motion can be controlled by delayed multiple detonations, either within each line source or between groups of line sources; and (4) no surface eruptions are produced by the detonation.

The array in a full-scale test might measure 100 x 30 ft, consist of 10 to 20 vertical bore holes 30 ft deep, spaced on 5- to 10-ft centers, and be placed about 30 ft from the structure to be tested. The full-scale source will be about 12 in. in diameter.

C. Results Summary

During the past year, a 1/3-scale developmental line source was designed and tested. The initial tests were performed with the developmental line source buried in a sand pit. During these tests, reusable hardware for producing contained explosions was developed, and instrumentation for measuring hardware performace and ground motion was checked.

The sand pit tests showed that bladder expansions of more than 2 times the initial bladder diameter were possible and that repeatable results were obtainable.

Tests were then performed with the developmental line source in soil. These tests showed reasonable accelerations (~0.8 g) and reasonable frequencies (~15 hz) were obtained in the soil with the 1/3-scale source.* Again, repeatable results were obtained.

Calculations were performed for an array of sources using a nonlinear finite element computer code. The measured single-source performance and ground response were used to develop a model for the source and to determine material properties for the soil. A reasonable agreement between measured and calculated soil response was obtained. Then, the model and properties were used to calculate ground motion for an array of sources.

This array calculation and accompanying theory were used to estimate the amount of explosive required to give the desired plane wave free-field motion. The estimate showed that in a 100- x 30-ft array, a 5-Hz pulse with a 0.5-g peak acceleration can be produced with about 100 lb of explosive. A complete train of oscillations typical of strong earthquake motion lasting 10 s and peak accelerations reaching 1 g was estimated to require about 500 lb of explosive, fired in 10 detonations.

D. Recommendations for Future Work

Single 1/3-scale line sources have been successfully tested, and calculations show that an array of line source will produce a pulse of useful magnitude and frequency. As logical steps in the continued development of this simulation technique, we recommend performing array tests, using about 10 line sources at 1/3-scale, and designing and testing a single full-scale line source. The array tests would be

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*To obtain the expected full-scale values, divide acceleration and frequencies by 3.

used to develop techniques and to verify the array calculations. The single full-scale line source would then be designed and tested as the first step toward an array test with full-scale line sources.

II DESCRIPTION OF LINE SOURCE AND INSTRUMENTATION

A. Developmental Line Source

A sketch of the developmental line source is shown in Figure 2. The source is 1/3-scale of what we envision is required for a full-scale line source. The essential features are a closed, expandable rubber bladder and a vented steel canister in which the explosive is detonated. The explosion products flow out of the canister through vents to pressurize the bladder at a controlled rate. To keep the bladder from leaking, steel bladder supports are fitted to the top and bottom. A thick rubber sleeve is used to prevent the rubber from tearing at these steel supports.

The bladder was fabricated from 40 durometer pure gum rubber. We determined early in the test program that synthetic rubbers such as neoprene are quite strain rate dependent. At strain rates of less than 20 in./in./min, neoprene can expand 300 to 400%, whereas at the strain rates required for source performance (1000 in./in./min) failure occurs at less than 100% expansion. Pure gum rubber is less sensitive to strain rate and therefore high strains are still possible at the high strain rate required.

The steel canister has a series of ports into which vent plugs can be fitted. These vent plugs serve two purposes: They redirect the flow from the canister away from the bladder so that the hot explosive gases do not burn the rubber, and they allow the canister vent area to be readily changed.

The upper bladder support contains two pressure gage ports through which internal bladder pressure is measured. Also, two small vents in the upper support vent the bladder to the atmosphere.

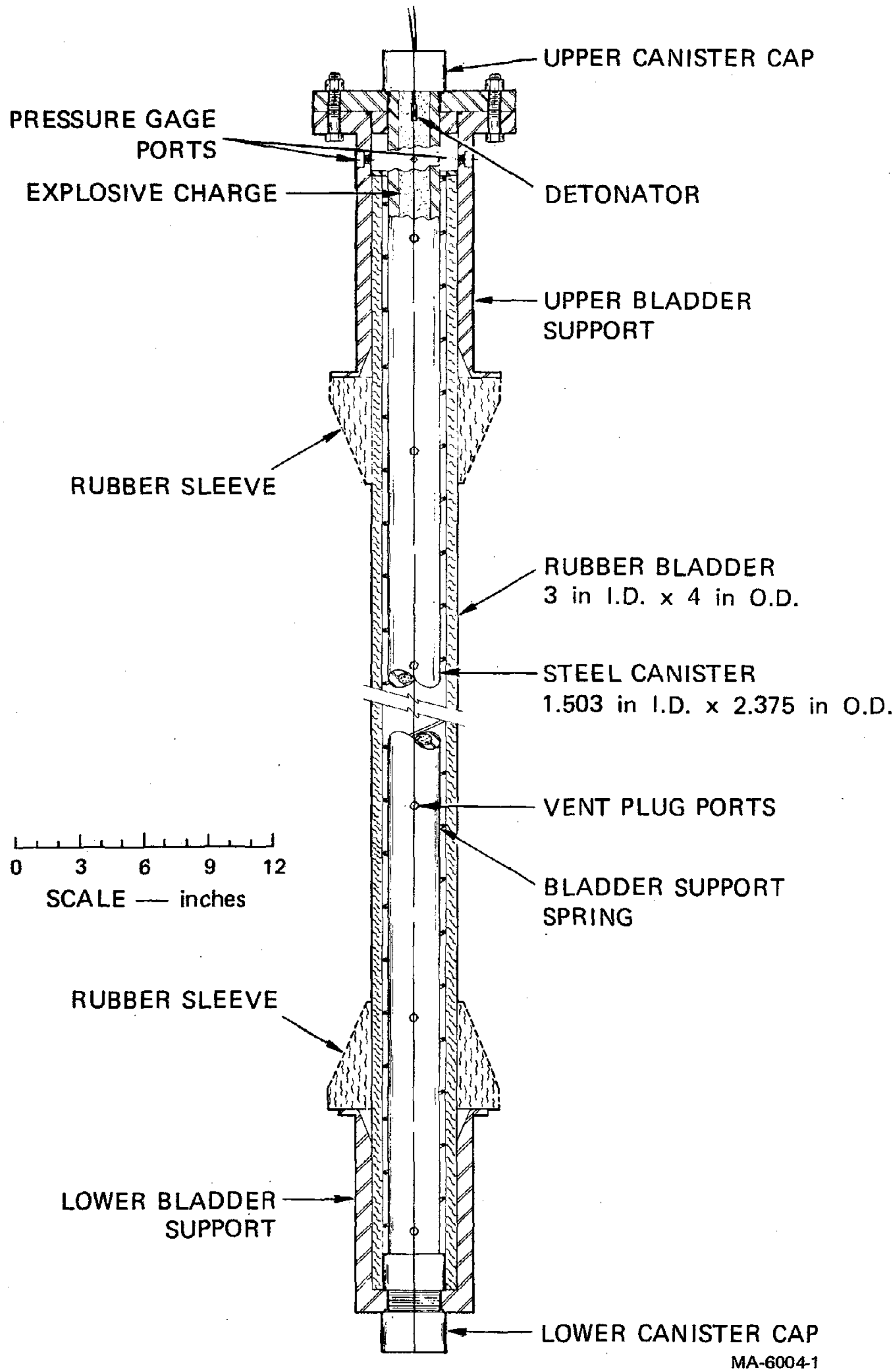


FIGURE 2 DETAILED ASSEMBLY DRAWING OF DEVELOPMENTAL LINE SOURCE

B. Instrumentation

Three types of instrumentation were used. Pressure gages were used to measure pressure inside the bladeer. A bladder expansion gage was developed and used to measure the bladder expansion as a function of time. Accelerometers were used to measure ground motion.

The bladder expansion gage consisted of a 2- x 6- x 0.016-in. steel sheet that was wrapped around the bladder and held in place with a thin rubber sleeve. A strain gage was used to determine the curvature change of the steel sheet and thus the diameter of the rubber bladder. This bladder expansion gage was calibrated in the laboratory and field-checked by comparison with a passive bladder expansion gage consisting of a wire with two slip connections fitted around the bladder. Terminal observation of the wire length gave the maximum bladder expansion during the test for comparison with the active gage.

III TEST RESULTS

A. Tests of Developmental Line Source in Sand Pit

A 6-ft-long version of the developmental line source described above was tested in a 6- x 6- x 6-ft sand pit. The objectives of these tests were to develop the hardware, check the instrumentation, and take a preliminary look at soil response. The sand pit allowed easy removal of the line source for inspection and for parts replacement with design improvements, as required.

Figure 3 is a schematic of the test arrangement. The line source was lowered into the pit, and the pit was backfilled with wet sand and tamped. Between tests, sand was removed from the pit to allow inspection of the bladder. If no parts changes or replacements were necessary, the pit was again backfilled and tamped without removing the source. The accelerometers were placed inside the pit at depths from 1 to 3 ft and distances of 2 to 6 ft from the source.

Figure 4 shows the results from one test in the sand pit, using 39 gm of explosive (Test 18). At this point, the hardware and the instrumentation were all operational. Pressure in the bladder rose to 90 psi in 4 ms, Figure 4(a). The diameter of the bladder expanded from 4 to 8 in. in 20 ms, Figure 4(b). Accelerations in the sand 26 in. from the source had a magnitude of 1.8 g and period of 25 ms, Figure 4(c). Essentially the same results were obtained in a repeat of Test 18, as shown in Figure 5.

B. Tests of Developmental Line Source in Soil

At the conclusion of the tests in the sand pit, the hardware and instrumentation were working and reproducible results were being obtained. The next step was to test the same 6-ft-long line source in soil. These tests were aimed at determining the effects of charge size and canister vent area on the magnitude and frequency of ground motion.

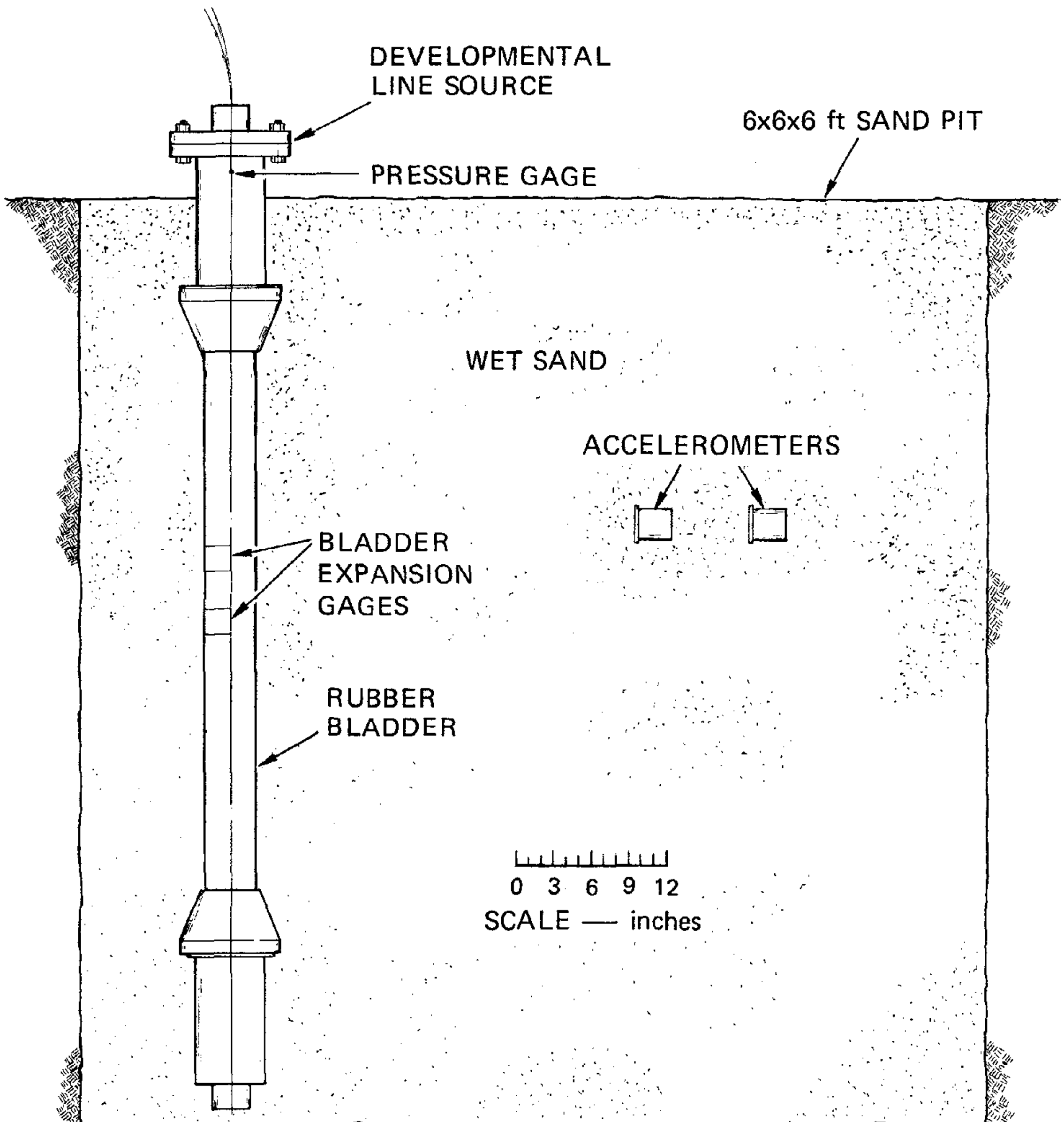
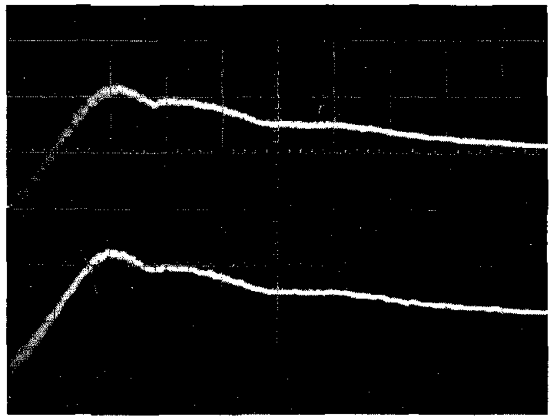
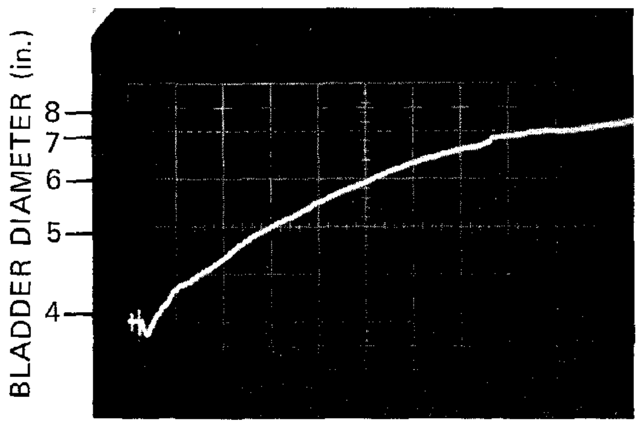


FIGURE 3 SCHEMATIC OF DEVELOPMENTAL LINE SOURCE IN SAND PIT



(a) PRESSURE IN BLADDER (40 psi/div, 2 ms/div)



(b) BLADDER EXPANSION (0.05% ε/div, 2 ms/div, 0.21% ε IN STEEL = 100% ε IN RUBBER)

(c) ACCELERATION 26 in. FROM SOURCE (1.0 g/div, 10 ms/div)

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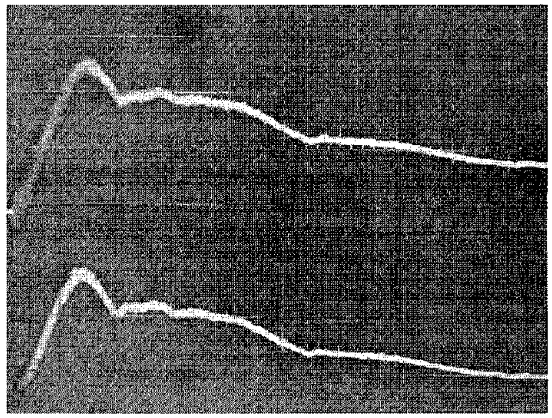
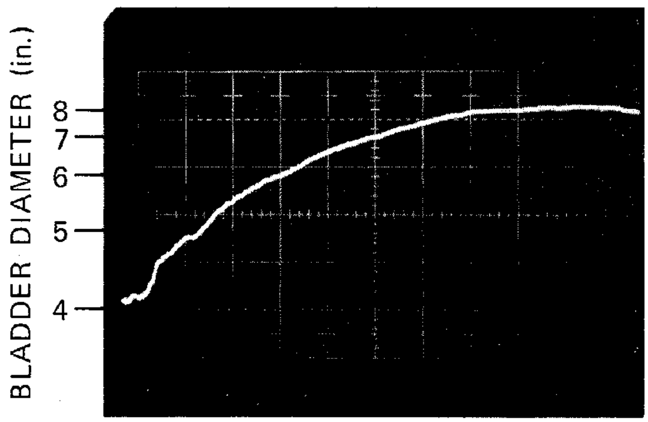
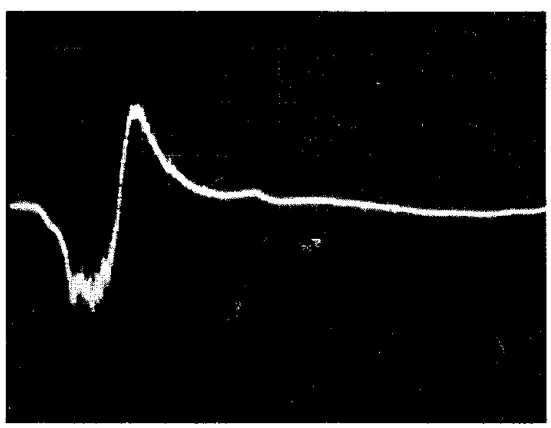
FIGURE 4 SOURCE PRESSURE, SOURCE EXPANSION, AND GROUND ACCELERATION (Test 18, Sand Pit, 39 gm PETN, Canister Vent Area = 0.75 in.^{2})



(a) PRESSURE IN BLADDER (40 psi/div, 2 ms/div)



(b) BLADDER EXPANSION (0.05% ϵ/div, 2 ms/div, 0.21% ϵ IN STEEL = 100% ϵ IN RUBBER)



(c) ACCELERATION 26 in. FROM SOURCE (1.0 g/div, 10 ms/div)

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FIGURE 5 SOURCE PRESSURE, SOURCE EXPANSION, AND GROUND ACCELERATION (Test 19, Sand Pit, 39 gm PETN, Canister Vent Area = 0.75 in.^{2})

Figure 6 is a schematic of the line source in soil. The source was placed in a 6-ft-deep, 12-in.-diameter hole and backfilled with saturated sand. The sand and water were backfilled in the layers and then tamped to achieve compaction for good coupling. During a test the source compacts the surrounding sand. The source was not removed from the hole between repeated tests, but the surrounding sand was repacked around the source, and resaturated. The explosive charge was then loaded from the surface. However, it was necessary to remove the source to change the canister vent area; this was readily done using a forklift once the source had expanded the surrounding sand. (Future design changes to allow canister vent area changes without removing the source are planned.) Accelerometers were placed in 4-in.-diameter holes that were backfilled with saturated sand to ensure good coupling to the soil. They were placed at depths from 1 to 3 ft and distances of 4 to 10 ft from the source. Because no significant difference in acceleration was measured at these different depths, most accelerometer records were made at a depth of 2 ft.

Tests were performed at two sites, SRI's Corral Hollow Experimental Site (CHES) and a site in Menlo Park. The primary reason for moving to the Menlo Park site was the nonuniformity of the soil at CHES. During the early tests at CHES, we found that there was very little noise, no cratering, and no thrown debris from a test because the explosive products are contained within the bladder. This allowed the tests to be performed at SRI's suburban Menlo Park location.

Figure 7 shows ground accelerations from three tests at CHES using a canister vent area of 0.11 in.^{2}. (These records were digitized from oscillograph traces.) Figure 7(a) shows the acceleration record 58 in. from the source using 39 gm of explosive. Figures 7(b) and (c) show the repeatability of acceleration at the same distance for two shots each with a charge of 58 gm. (To repeat a test the source is not removed from the hole, but the surrounding sand is repacked around the source and resaturated.) Comparison of Figure 7(a) with either 7(b) or (c) shows that acceleration amplitude increases with charge, but duration and pulse shape remain about the same.

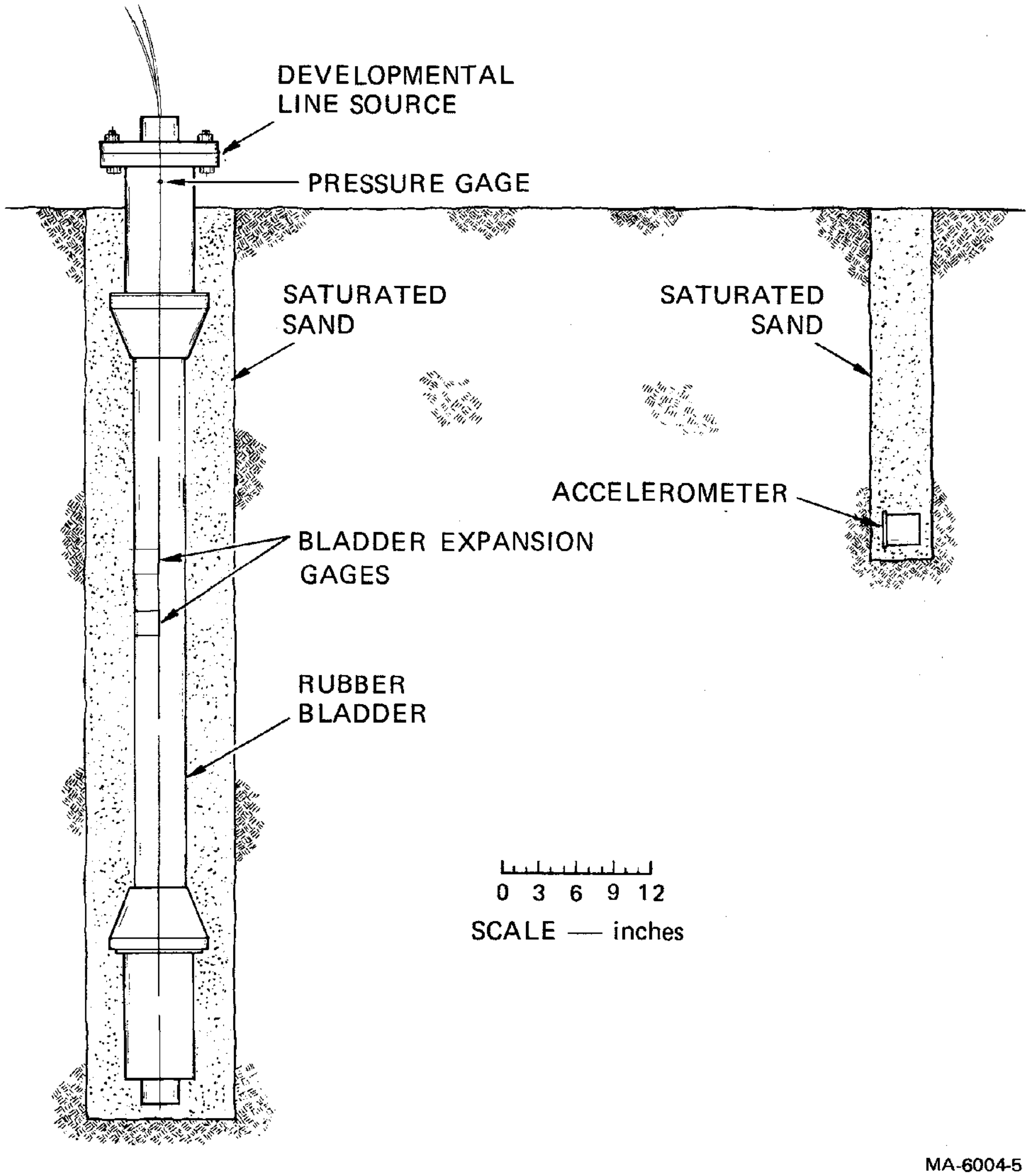
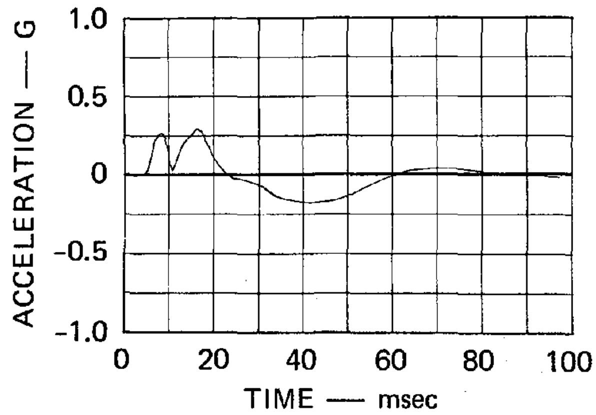
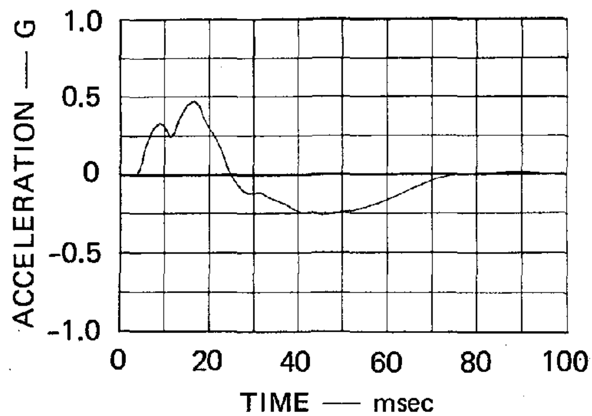


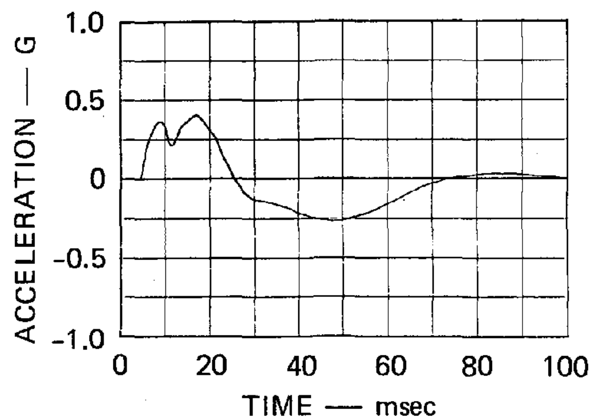
FIGURE 6 SCHEMATIC OF DEVELOPMENTAL LINE SOURCE IN SOIL



(a) **TEST 29, 39 gms PETN, A1 (58 in. FROM SOURCE)**



(b) **TEST 30, 58 gms PETN, A1 (58 in. FROM SOURCE)**



(c) **TEST 31, 58 gms PETN, A1 (58 in. FROM SOURCE)**

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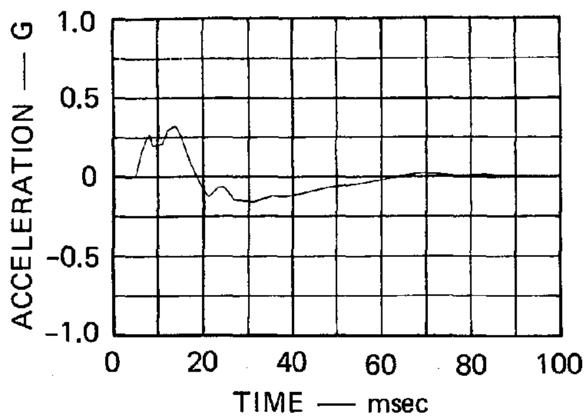
FIGURE 7 VARIATION OF EARTH MOTION WITH AMOUNT OF PETN
(Location: CHES Area 1, Canister Vent Area: 0.11 in.^{2})

A key point in Figure 7 is that these are useful acceleration levels (0.45 g) and a useful period range (60 ms). Scaling laws indicate that if the developmental line source is scaled up by a factor of 3 for the full-scale line source, the acceleration magnitude will decrease by a factor of 3 (to 0.15 g), and the period will increase by the same factor of 3 (to 200 ms). These values are for a single line source and, therefore, give only a lower bound on results expected from plane array. (Further explanation of this observation and the theoretical extrapolation to array geometry are given in Section IV).

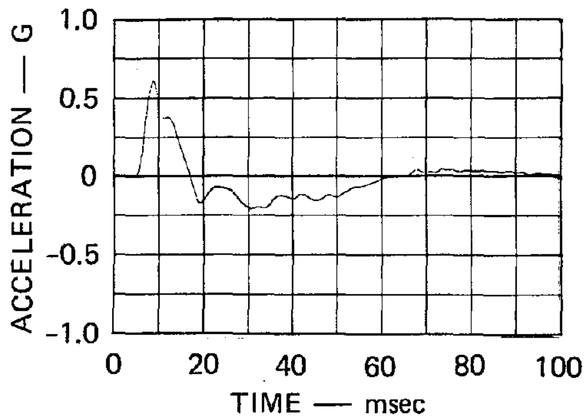
Figure 8 shows ground accelerations 57 in. from the source at the Menlo Park site, again using a canister vent area of 0.11 $in.^2$. Charges of 39, 58, and 78 gm were used to give the records shown in Figures 8(a), (b), and (c), respectively. Again, acceleration amplitude increases with charge. Comparison of Figures 7 and 8 demonstrates that the records at CHES and Menlo Park are similar.

Figure 9 shows ground accelerations 63 in. from the source for the Menlo Park site, with a canister vent area of 0.17 $in.^2$,--a 50% increase in vent area over that for Figure 8. (These records were digitized from magnetic tape by using an analog-to-digital program.) For Figure 9(a), the charge was 39 gm. For Figure 9(b) and (c), the charge was 58 gm. Comparison of Figures 8 and 9 shows that the increased canister vent area gave higher acceleration levels but not shorter duration. Again the results were repeatable, and acceleration amplitude increased with charge.

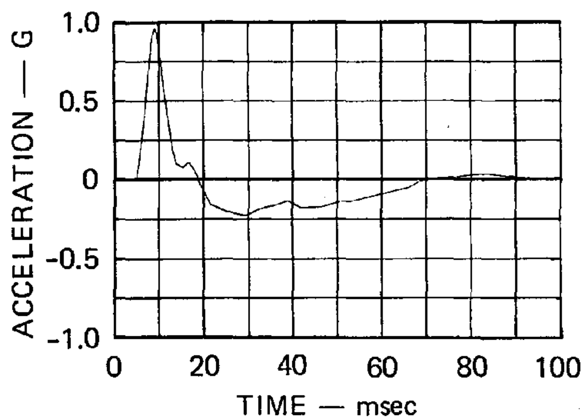
Figure 10 shows the variation of bladder pressure and ground acceleration with changes in the canister vent area. All these results are from the Menlo Park site with 58 gm of explosive in each test. Accelerations were measured approximately 60 in. from the source. Figure 10(a), (c), and (e) show the bladder pressure with canister vent areas of 0.17, 0.11, and 0.06 $in.^2$, respectively. Figures 10(b), (d), and (f) show the corresponding ground acceleration. Decreasing the canister vent area increases the rise time of bladder pressure, as desired. However, essentially no change in ground motion frequency occurs. We believe



(a) TEST 41, 39 gms PETN, A3 (57 in. FROM SOURCE)



(b) TEST 43, 58 gms PETN, A3 (57 in. FROM SOURCE)



(c) TEST 44, 78 gms PETN, A3 (57 in. FROM SOURCE)

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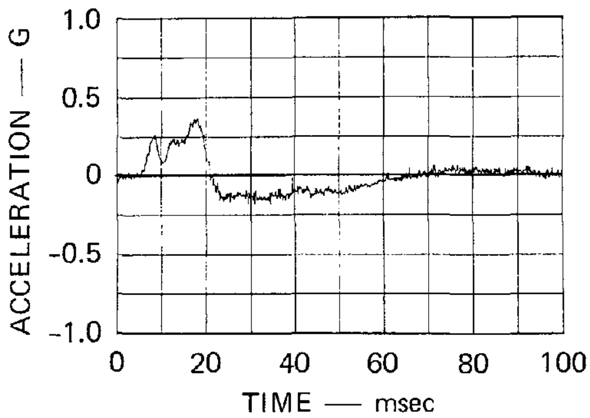
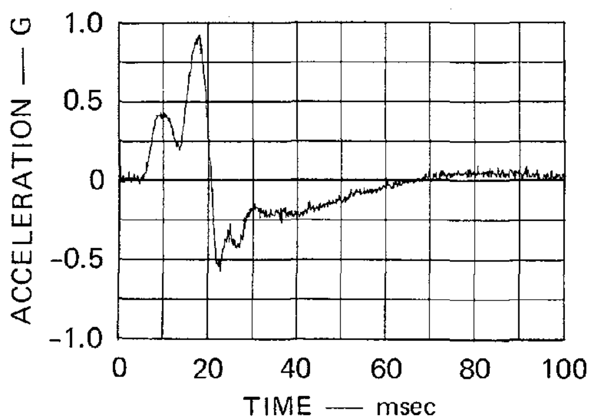
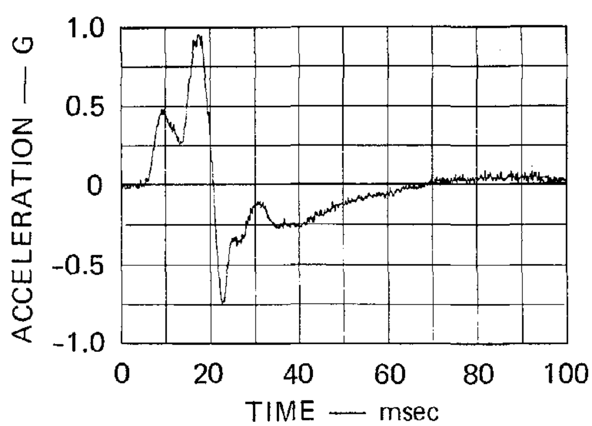
FIGURE 8 VARIATION OF EARTH MOTION WITH AMOUNT OF PETN
(Location: Menlo Park, Canister Vent Area: 0.11 in.^{2})



(a) TEST 48, 39 gms PETN, A1 (63 in. FROM SOURCE)



(b) TEST 49, 58 gms PETN, A1 (63 in. FROM SOURCE)



(c) TEST 50, 58 gms PETN, A1 (63 in. FROM SOURCE)

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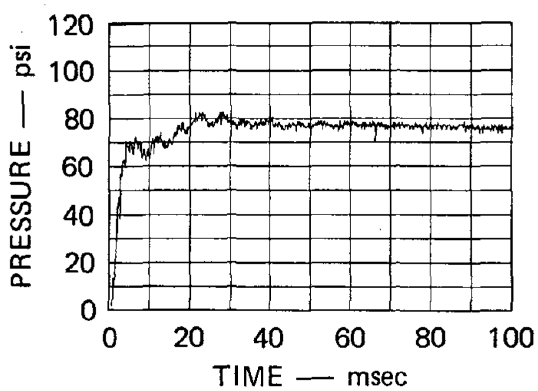
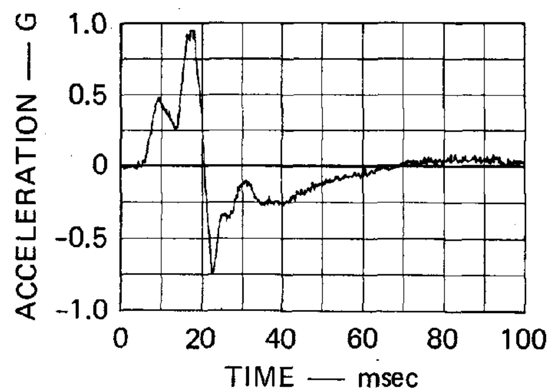
FIGURE 9 VARIATION OF EARTH MOTION WITH AMOUNT OF PETN

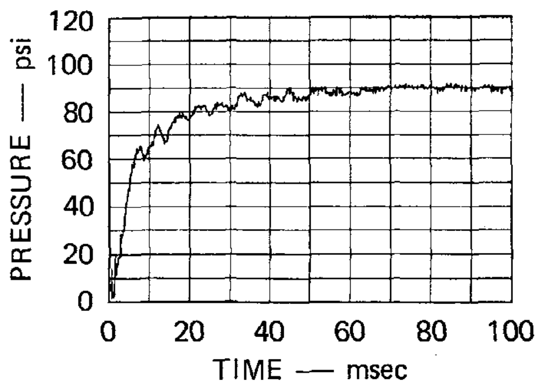
(Location: Menlo Park, Canister Vent Area = 0.17 in.^{2})



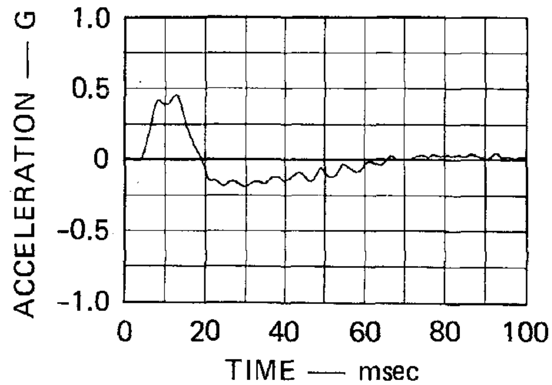
(a) SOURCE PRESSURE (TEST 50, CANISTER VENT AREA = 0.17 in.^{2})



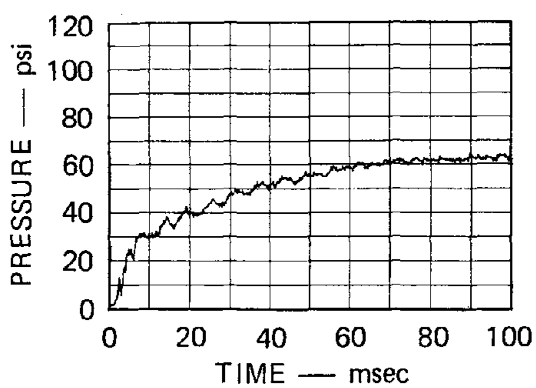
(b) ACCELERATION (TEST 50, 63 in. FROM SOURCE)



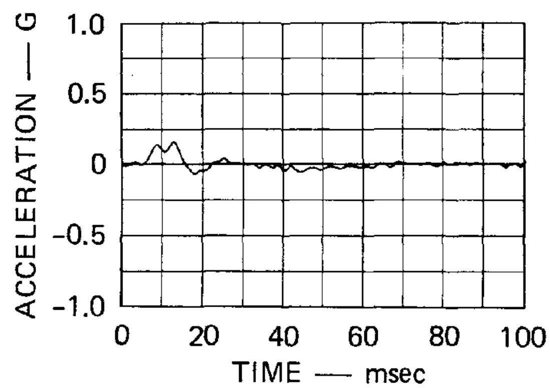
(c) SOURCE PRESSURE (TEST 43, CANISTER VENT AREA = 0.11 in.^{2})



(d) ACCELERATION (TEST 43, 58 in. FROM SOURCE)



(e) SOURCE PRESSURE (TEST 46, CANISTER VENT AREA = 0.06 in.^{2})



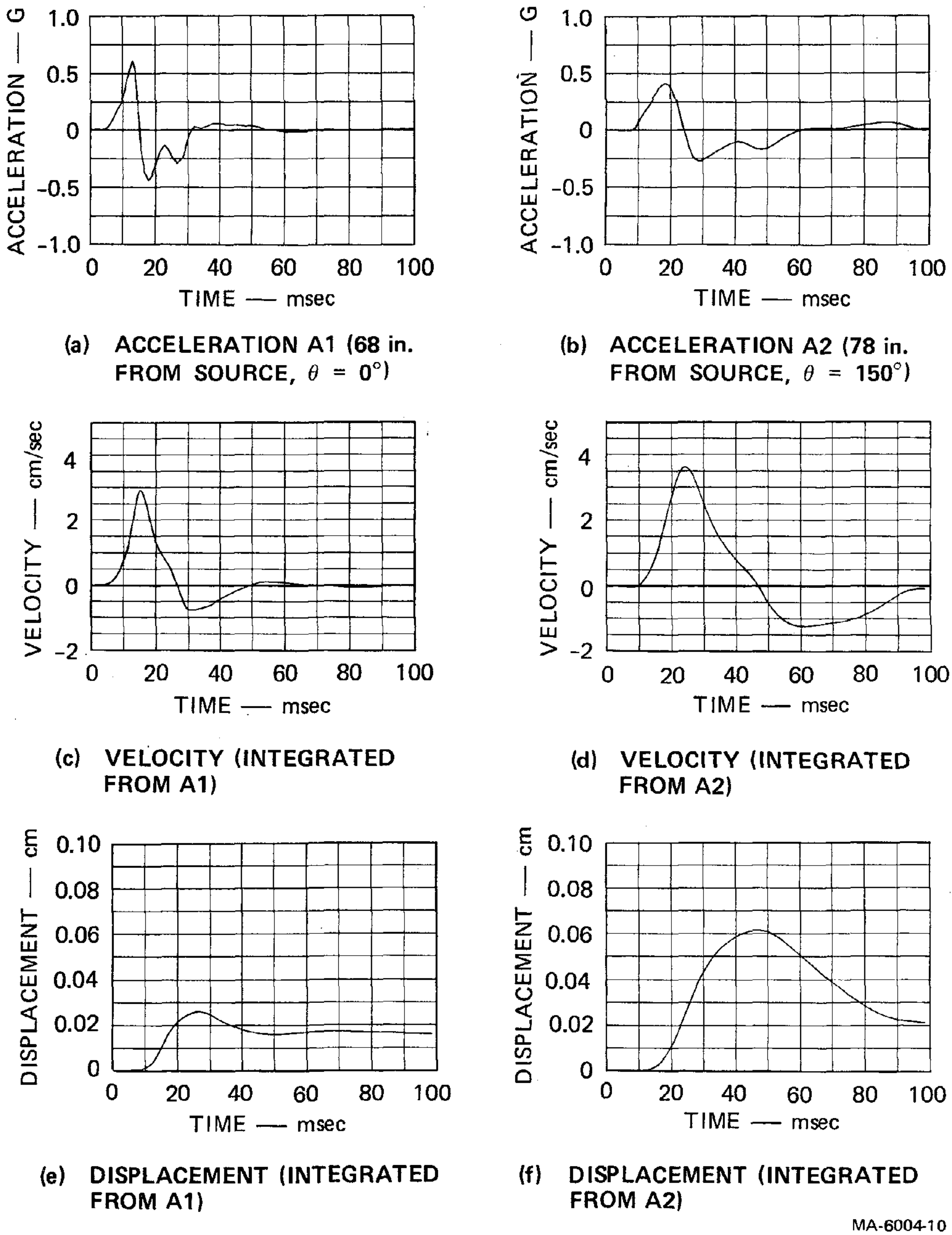
(f) ACCELERATION (TEST 46, 59 in. FROM SOURCE)

MA-6004-9

FIGURE 10 VARIATION OF SOURCE PRESSURE AND EARTH MOTION WITH CANISTER VENT AREA (Location: Menlo Park, 58 gms PETN) that this may be attributed to the large contribution of soil hoop strength for the cylindrical geometry of a single source. Dominance of hoop strength is evidenced by the quick oscillation of acceleration to a negative phase, whereas bladder pressure remained nearly constant. In plane geometry, the acceleration becomes negative only when the pressure is reduced.

Figure 11 shows the variation of ground motion with direction from the source at CHES. This test used 39 gm of explosive and had a canister vent area of 0.33 $in.^2$. Figures 11(a) and (b) show the records from accelerometers A1 and A2. Accelerometer A1 was 68 in. from the source, and A2 was 78 in. from the source, at a direction offset 150° from that of A1. The variation of frequency content of the ground acceleration with direction from the source is attributed to the nonuniformity of soil at CHES. Figures 11(c) through (f) show the velocity and displacement-time histories for the two gage locations, calculated by integrating the acceleration records. Again, the variation of motion with direction can be seen.

Figure 12 shows the variation of ground motion with direction from the source at Menlo Park. Here, we felt that the soil was more uniform. This test used 58 gm of explosive and had a canister vent area of 0.17 $in.^2$. Figures 12(a) and (b) show the records from two accelerometers, A1 and A4, located approximately 60 in. from the source and offset 180° from each other. Figures 12(c) through (f) show the calculated velocity and displacement-time histories for the two locations. The accelerations differ somewhat in magnitude and shape with direction from the source, but there is a uniformity of frequency content and duration, and the integrated accelerations (velocities) are quite similar in both magnitude and duration. This agreement in velocity and in displacement-time histories indicates the symmetry of the ground motion around the source.



(a) ACCELERATION A1 (68 in. FROM SOURCE, θ = 0°)

(b) ACCELERATION A2 (78 in. FROM SOURCE, θ = 150°)

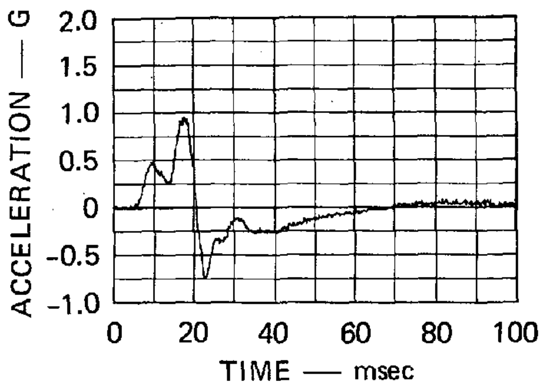
(c) VELOCITY (INTEGRATED FROM A1)

(d) VELOCITY (INTEGRATED FROM A2)

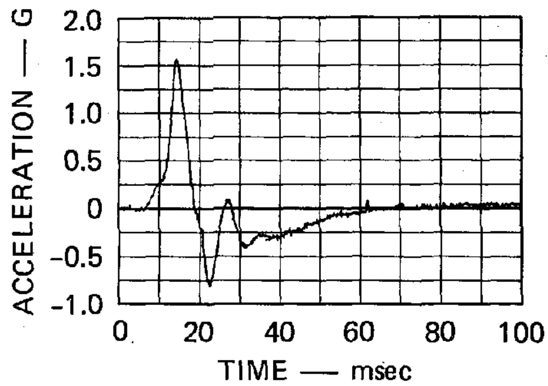
(e) DISPLACEMENT (INTEGRATED FROM A1)

(f) DISPLACEMENT (INTEGRATED FROM A2)

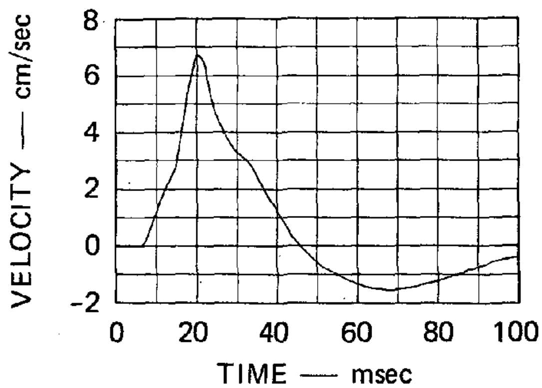
FIGURE 11 VARIATION OF EARTH MOTION WITH DIRECTION FOR CHES AREA 1
(Test 27, 39 gms PETN, Canister Vent Area 0.33 in.^{2})



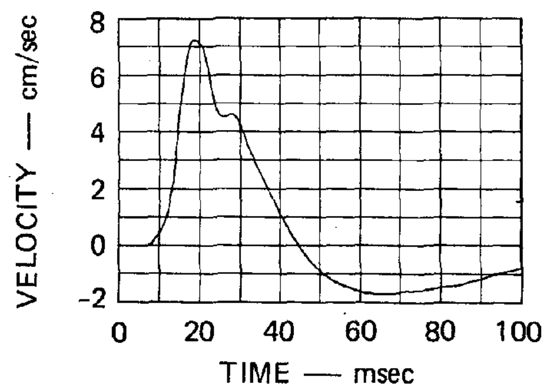
(a) ACCELERATION A1
(63 in. FROM SOURCE, θ = 0°)



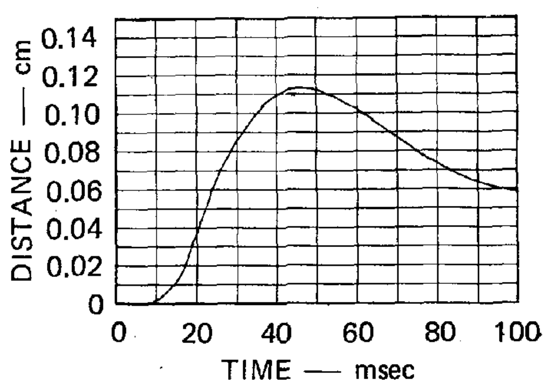
(b) ACCELERATION A4
(58 in. FROM SOURCE, θ = 180°)



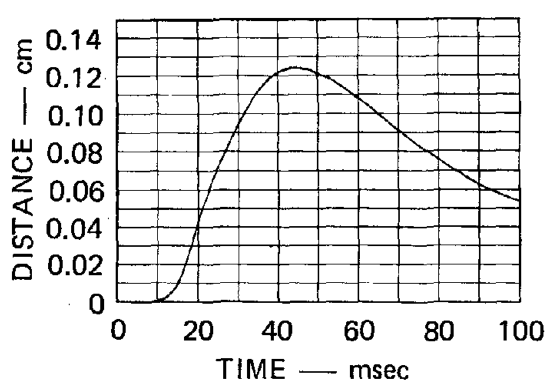
(c) VELOCITY
(INTEGRATED FROM A1)



(d) VELOCITY
(INTEGRATED FROM A4)



(e) DISPLACEMENT
(INTEGRATED FROM A1)



(f) DISPLACEMENT
(INTEGRATED FROM A4)

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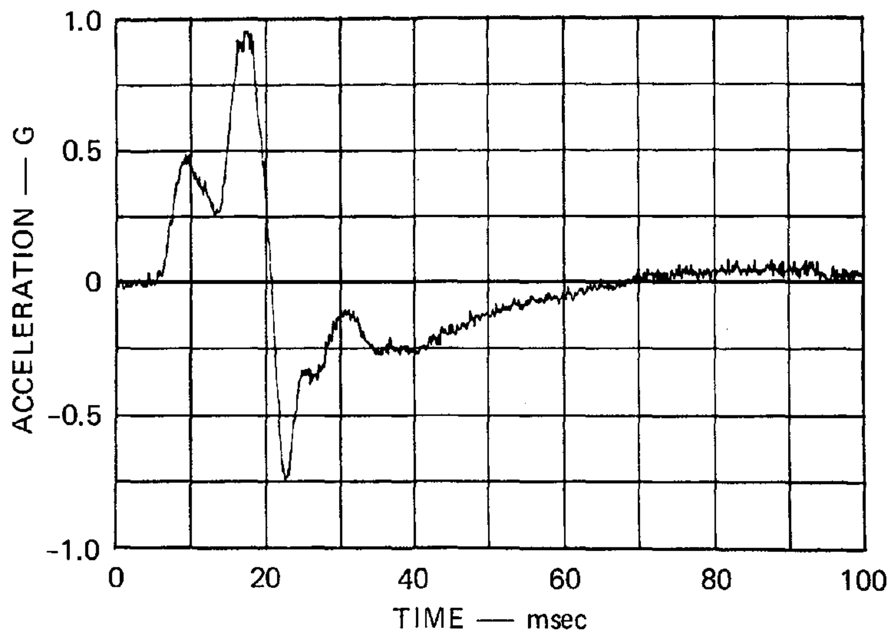
FIGURE 12 VARIATION OF EARTH MOTION WITH DIRECTION FOR MENLO PARK SITE
(Test 50, 58 gms PETN, Canister Vent Area = 0.17 in.^{2})

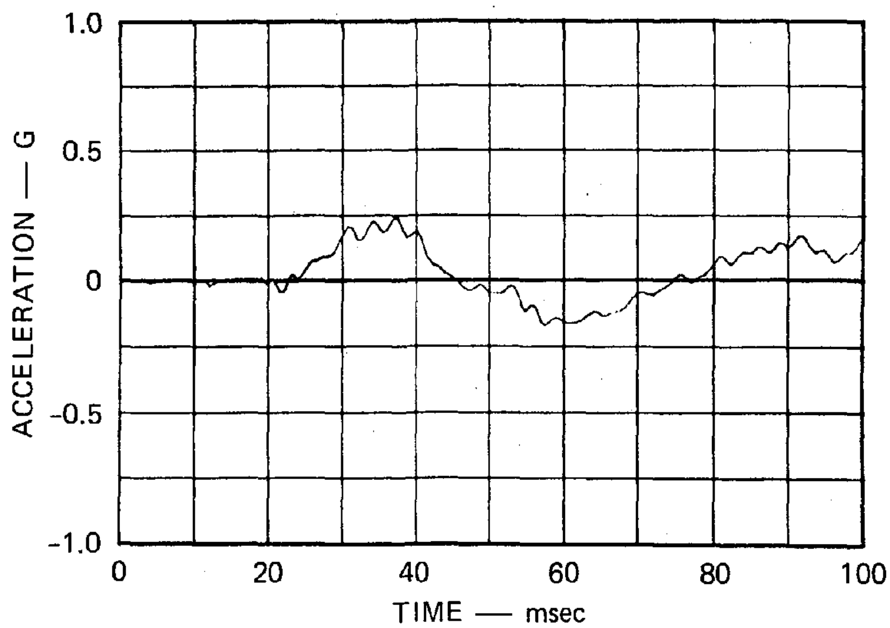
Figure 13 shows the ground acceleration for Test 50 from two accelerometers: A1, 63 in. from the source; and A2, 130 in. from the source. Here, 58 gm of explosive was used with a canister vent area of 0.17 in.^{2}. As expected for a single source, the acceleration amplitude decreases with range. The pulse duration remains the same, and pulse is smoothed with distance.

Figure 14 compares the horizontal and vertical accelerations at the same location for Test 50. The vertical acceleration is of similar magnitude but of higher frequency than the horizontal acceleration. This comparison probably depends on the line source length and the measuring location and should therefore be considered only as a first look.

Figure 15 shows results from Test 44, using 78 gm of explosive and a canister vent area of 0.11 in.^{2}. At late time, the rubber bladder split near the ground surface, causing a rapid decrease in pressure. This event gave new and useful information for possible improved source performance over that in which the gas is vented slowly to the atmosphere. Figures 15(a) through (e) show bladder pressure and ground response during loading (i.e., during pressure rise and before the bladder split). Sometime after 100 ms, the rubber bladder split. Figure 15(e) through (h) show bladder pressure and ground response during unloading (i.e., during pressure decay). Equal amounts of ground motion were generated in both loading and unloading, indicating the large amount of energy held in the "hoop" mode of the soil for a single source. This result also suggests a mechanism for getting repeated pulses from a single source; the bladder could be repeatedly pressurized and vented to the atmosphere in a controlled manner.



(a) **TEST 50 A1 (63 in. FROM SOURCE)**



(b) **TEST 50 A2 (130 in. FROM SOURCE)**

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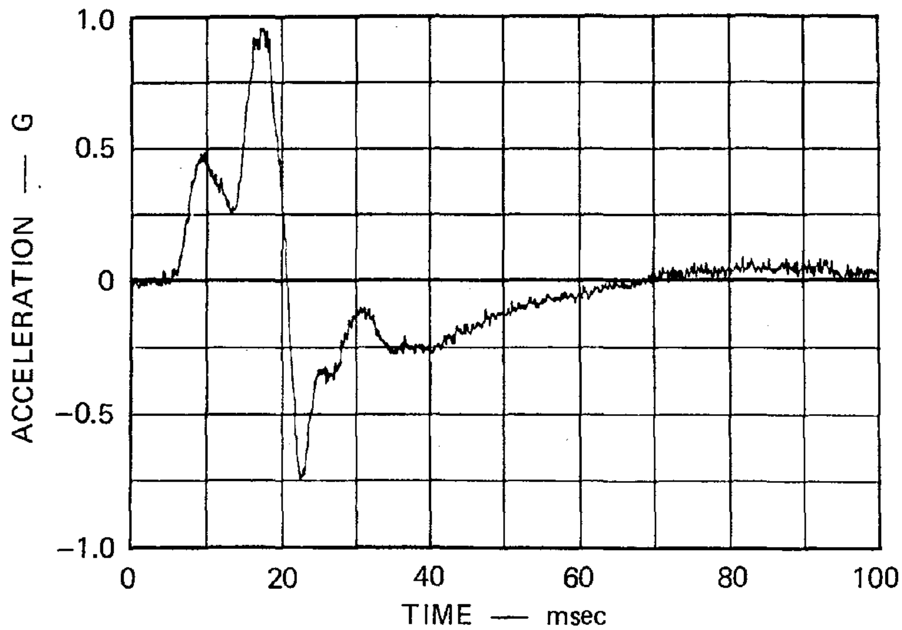
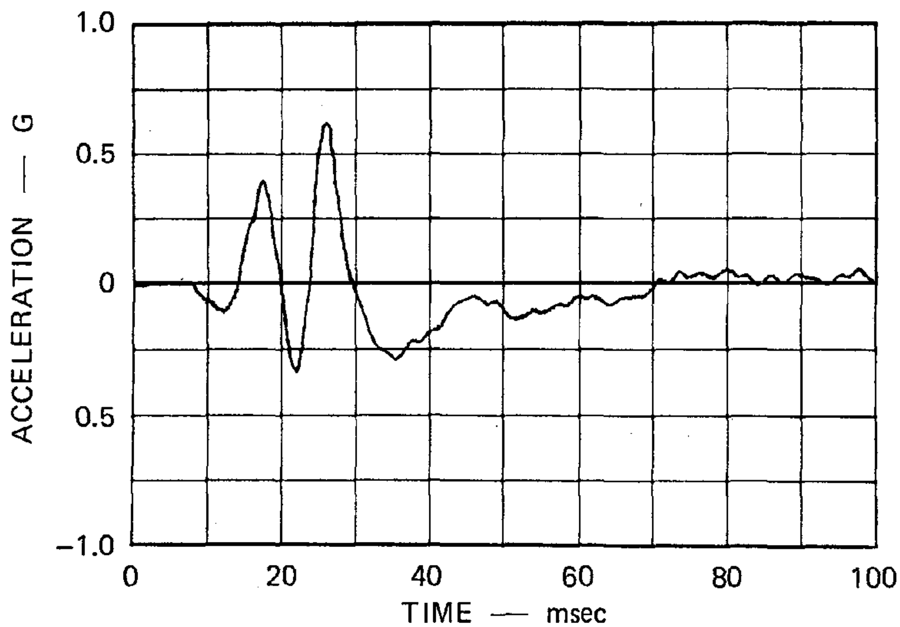
FIGURE 13 VARIATION OF EARTH MOTION WITH DISTANCE FROM SOURCE
(Test 50, Location: Menlo Park, 58 gms PETN, Canister Vent Area = 0.17 in.^{2})



(a) HORIZONTAL ACCELERATION, A1 (63 in. FROM SOURCE)



(b) VERTICAL ACCELERATION, A3 (63 in. FROM SOURCE)

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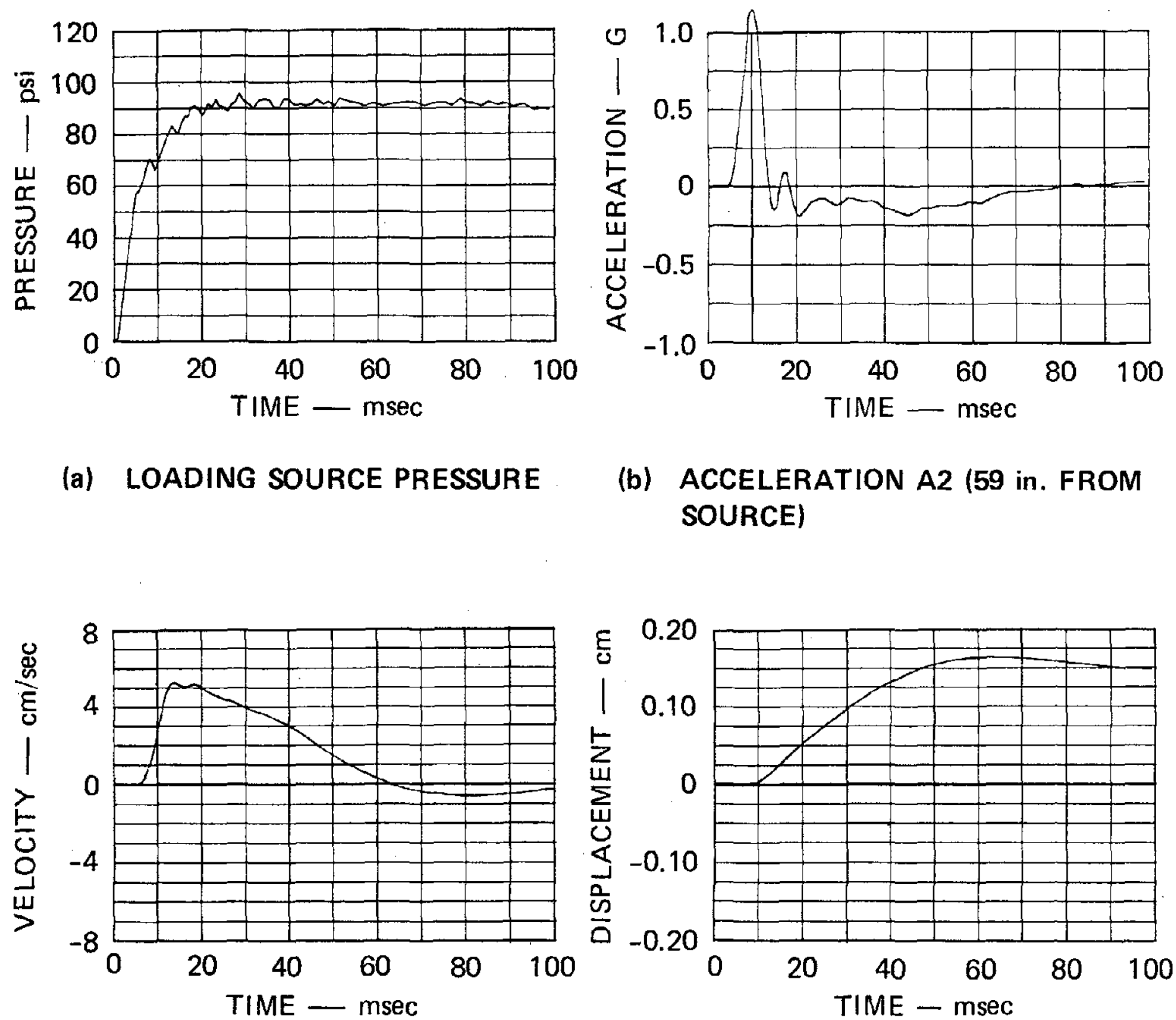
FIGURE 14 COMPARISON OF HORIZONTAL AND VERTICAL ACCELERATIONS (Test 50, Location: Menlo Park, 58 gms PETN, Canister Vent Area 0.17 in.^{2})



(a) LOADING SOURCE PRESSURE

(b) ACCELERATION A2 (59 in. FROM SOURCE)

(c) VELOCITY (INTEGRATED FROM A2)

(d) DISPLACEMENT (INTEGRATED FROM A2)

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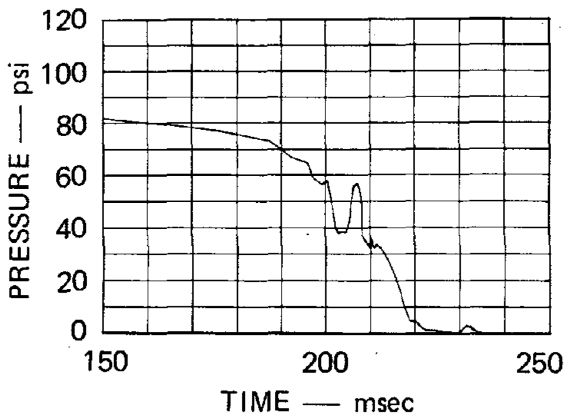
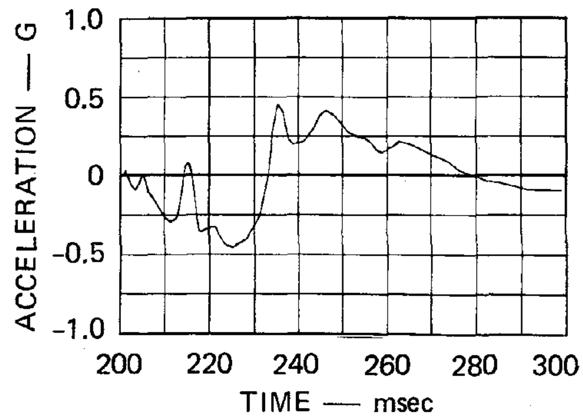
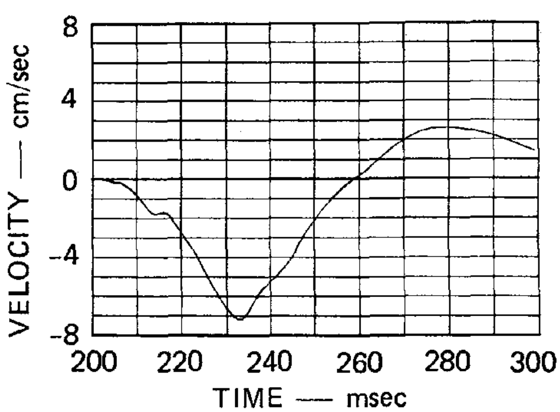
FIGURE 15 EARTH MOTION GENERATED BY SOURCE UNLOADING
(Test 44, Location: Menlo Park, 78 gms of PETN, Canister Vent Area = 0.11 in.^{2})



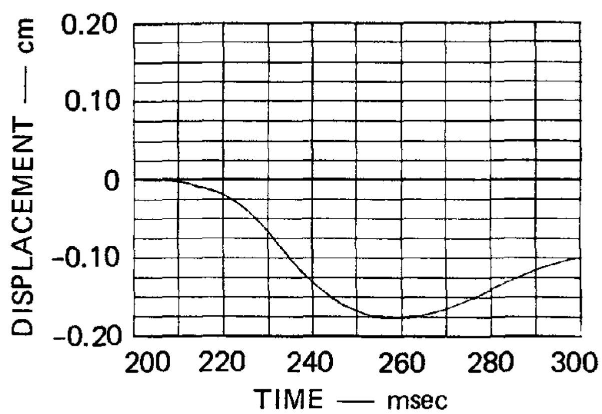
(e) **UNLOADING SOURCE PRESSURE**



(f) **ACCELERATION A2 (59 in. FROM SOURCE)**



(g) **VELOCITY (INTEGRATED FROM A2)**



(h) **DISPLACEMENT (INTEGRATED FROM A2)**

MA-6004-15

FIGURE 15 EARTH MOTION GENERATED BY SOURCE UNLOADING (Concluded)

IV CALCULATION OF GROUND MOTION FOR A PLANE ARRAY OF SOURCES

Ground motion for an array of sources was calculated in two steps. First, measured single-source performance and ground response were used to develop a model for the source and to determine material properties for the soil. Then, the model and properties were used in an array calculation.[4] A Mohr-Coulomb yield criterion and a stiffness-proportional damping formulation were used. The Mohr-Coulomb yield model has been used at SRI to calculate the response of rock and soil-type materials with good success on studies of deep-based[5,6] and shallow-buried structures[7] for the Defense Nuclear Agency. Energy absorbed by local soil compaction was taken into account by using as load input the actual measured bladder pressures, which are reduced by energy absorption of local compaction immediately around the bladder.

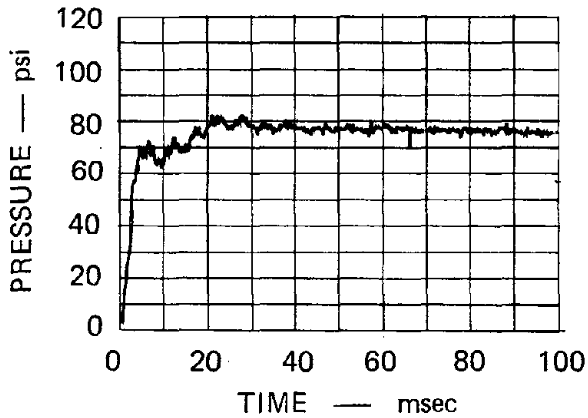
Material properties for the soil were chosen by matching the key features of computed and measured ground accelerations for a single source. Young's Modulus (E) was chosen by matching the arrival time. Poisson's ratio (ν), the angle of internal friction (ϕ), density (ρ), and the percentage of critical damping (β) were given values characteristic of soils in general. Peak ground acceleration and duration of the positive velocity phase could then be matched by choosing a value for the unconfined compressive strength (σ_u). Three iterations were required. The following material properties were used in the third iteration and in all subsequent calculations described below.

$E = 8100$ psi	$\sigma_u = 10$ psi
$\nu = 0.25$	$\rho = 115$ lb/ft
$\phi = 30°$	$\beta = 20\%$

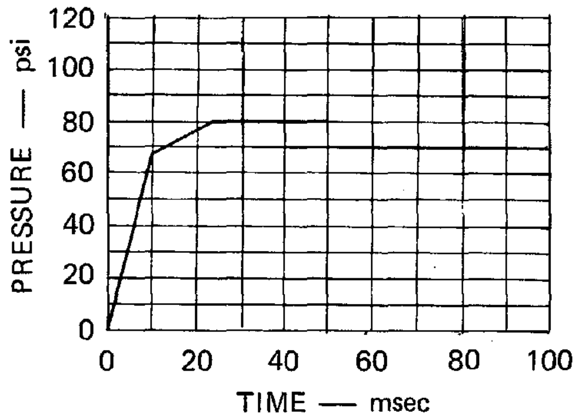
An axisymmetric mesh consisting of 6-node isoparametric elements with uniform 8-in. spacing was used to model the soil around a single source. The rubber bladder was not modeled; the input pressure was applied directly to a 4-in.-diameter hole in the soil. The comparison of recorded and calculated single source ground motion was made for Test 50 at Menlo Park, which used 58 gm of explosive and a canister vent area of 0.17 $in.^2$. Figure 16(b) shows the input pressure used for the NONSAP calculation. To achieve a better match between calculated and recorded ground motion, we slightly increased the rise time of the input pressure from that of the recorded bladder pressure, Figure 16(a). The need for this correction may be attributed to the compressibility of the sand immediately around the source, dictating a slower rise time in the soil than that measured in the bladder.

Figures 16(d) and (f) show the calculated acceleration and velocity records 60 in. from the line source. The oscillations in the later portion of the calculated acceleration record are attributable to the finite element size and to the fact that the accelerations are computed by twice differentiating the calculated nodal displacements. A reasonable agreement with the recorded ground motion, Figures 16(c) and (e), was obtained by using the material properties described above.

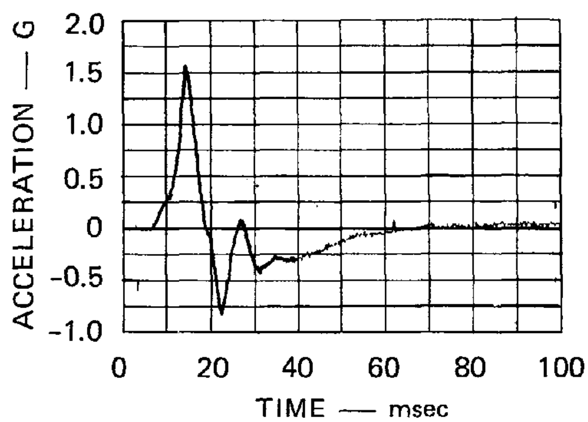
As a check of this material modeling, a comparison of the recorded and calculated single source ground motion was also made for Test 46 at Menlo Park, which used 58 gm of explosive and a canister vent area of 0.06 $in.^2$. Figure 17 (b) shows the input pressure used for the calculation. Again, the rise time of the input pressure was increased slightly from that of the recorded pressure, Figure 15(a). Additionally, the input pressure was decreased at late times to account for the hoop stress in the rubber bladder (when fully expanded, the bladder can carry up to 30 psi). Figures 17(d) and (f) show the calculated acceleration and velocity recorded 60 in. from the line source. Again, the oscillations in the later portion of the calculated acceleration record are attributed



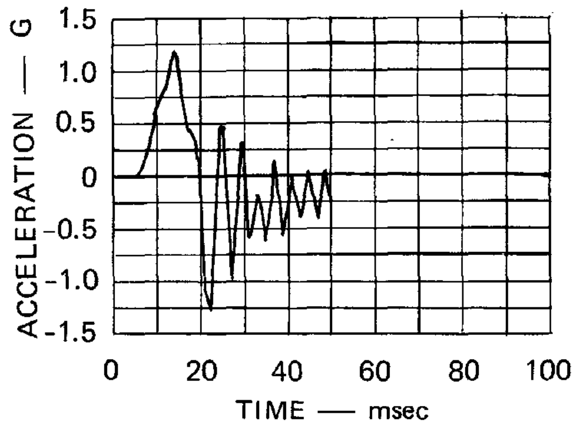
(a) RECORDED BLADDER PRESSURE (TEST 50)



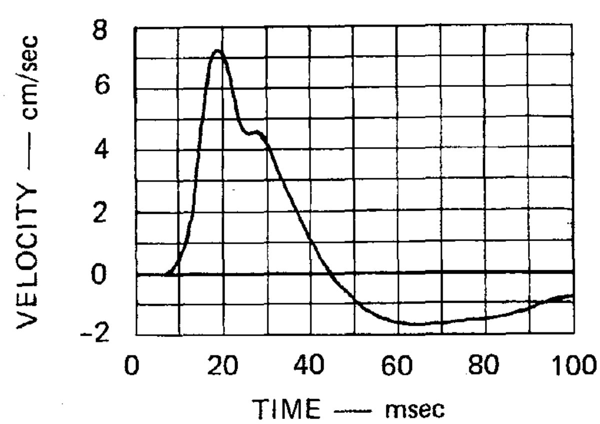
(b) INPUT PRESSURE (NONSAP CALCULATION)



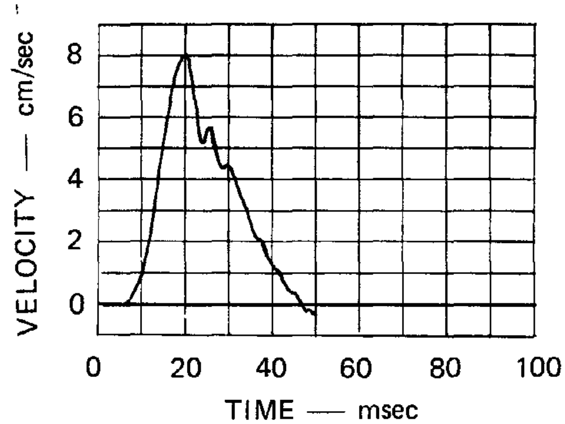
(c) RECORDED ACCELERATION (TEST 50, 58 in. FROM SOURCE)



(d) CALCULATED ACCELERATION (NONSAP 60 in. FROM SOURCE)



(e) VELOCITY (TEST 50, INTEGRATED FROM RECORDED ACCELERATION ABOVE)



(f) CALCULATED VELOCITY (NONSAP, 60 in. FROM SOURCE)

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FIGURE 16 COMPARISON OF SINGLE SOURCE RECORDED AND CALCULATED GROUND MOTION (Test 50, 58 gms PETN, Canister Vent Area = 0.17 in.^{2})

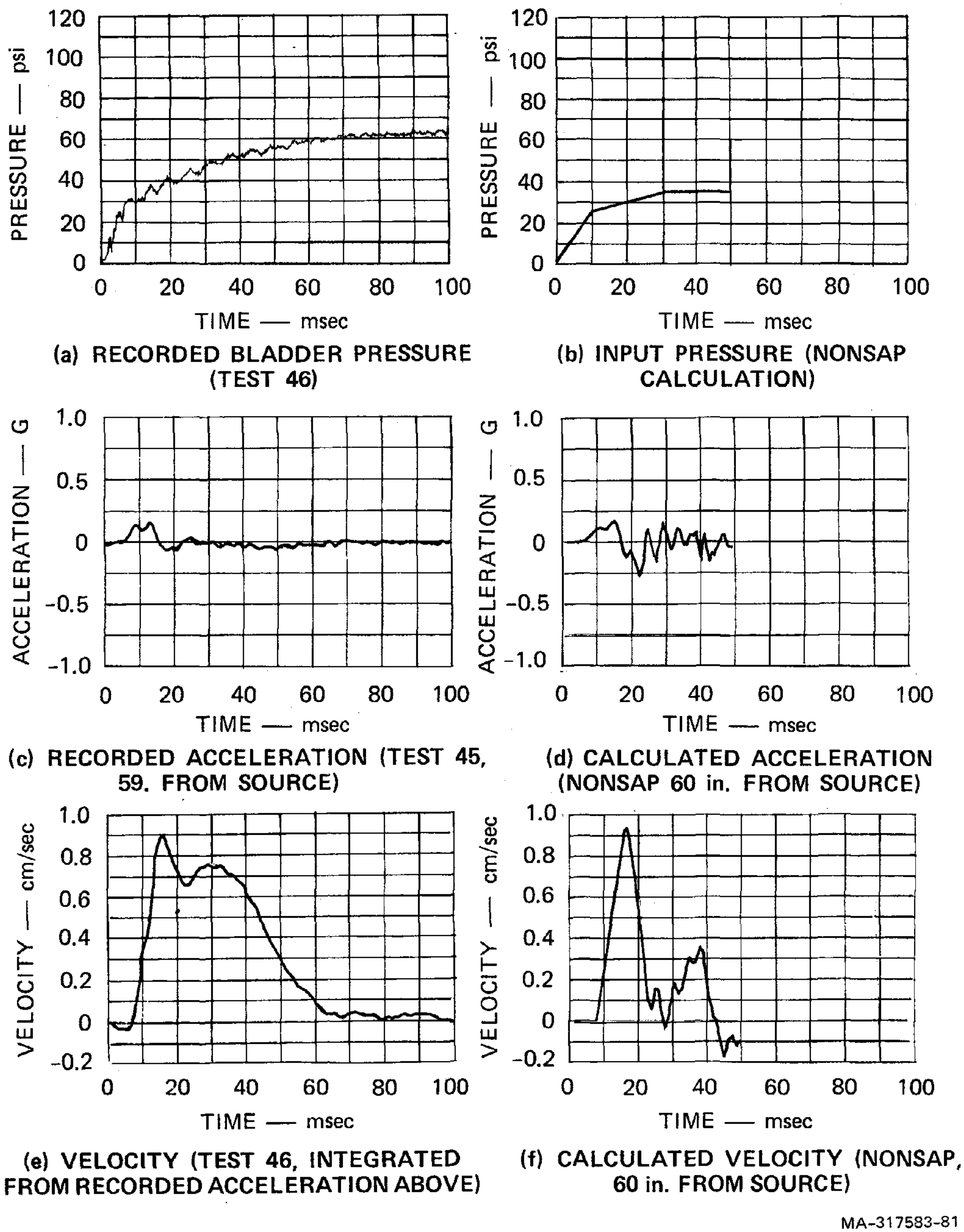


FIGURE 17 COMPARISON OF SINGLE SOURCE RECORDED AND CALCULATED GROUND MOTION (Test 46, 58 gms PETN, Canister Vent Area = 0.06 in.^{2})

to the numerical solution. Comparison of Figures 17(c) and (e) with (d) and (f) shows that a reasonable agreement between the calculated and measured ground motion was obtained. The late-time measured velocity falls off more slowly because, at this low level, small errors in acceleration baseline are are comparable to the acceleration level.

We concluded that the theoretical model gives a reasonable representation of the source and the soil behavior. The next step was to use this Mohr-Coulomb model in a two-dimensional calculation of the response of an array of sources. The same material properties were used as in the single-source calculations. A two-dimensional mesh consisting of 4-node isoparametric elements with 4-in. spacing was used to model the soil. To lower computation costs, we did not include the ends of the array and the soil free surface so that the calculation could be made over a material mesh between two infinite, imaginary, rigid planes perpendicular to the array and bisecting the distance between two adjacent line sources. By symmetry, the response of the entire array would be an infinitely repeated pattern of these basic meshes. Symmetry through the centerline of the source, both perpendicular and parallel to the array, further lowered the required mesh extent.

Ground motion was calculated for an array of 1/3-scale (4-in. diameter) sources spaced 2 ft apart from center to center. This corresponds to a 6-ft spacing in full scale, within the range envisioned in application. Figure 18(a) shows the idealized input pressure used for the calculation. The pressure rises bilinearly to 80 psi at 20 ms, then decays in the same manner to 0 psi at 40 ms. This pressure is similar to that measured in Test 50, except that it is allowed to decay after the first 20 ms. Therefore, this is a realistic pressure pulse that could be generated from a 58-gm charge in our 1/3-scale source.

Figures 18(b) and (d) show the calculated acceleration and velocity records at 60 in. from the source. Figure 18(c) shows the calculated velocity record at 20 in. from the source. Comparison of Figures 18(b) and (d) shows the ground motion to be nonattenuating and to behave as a

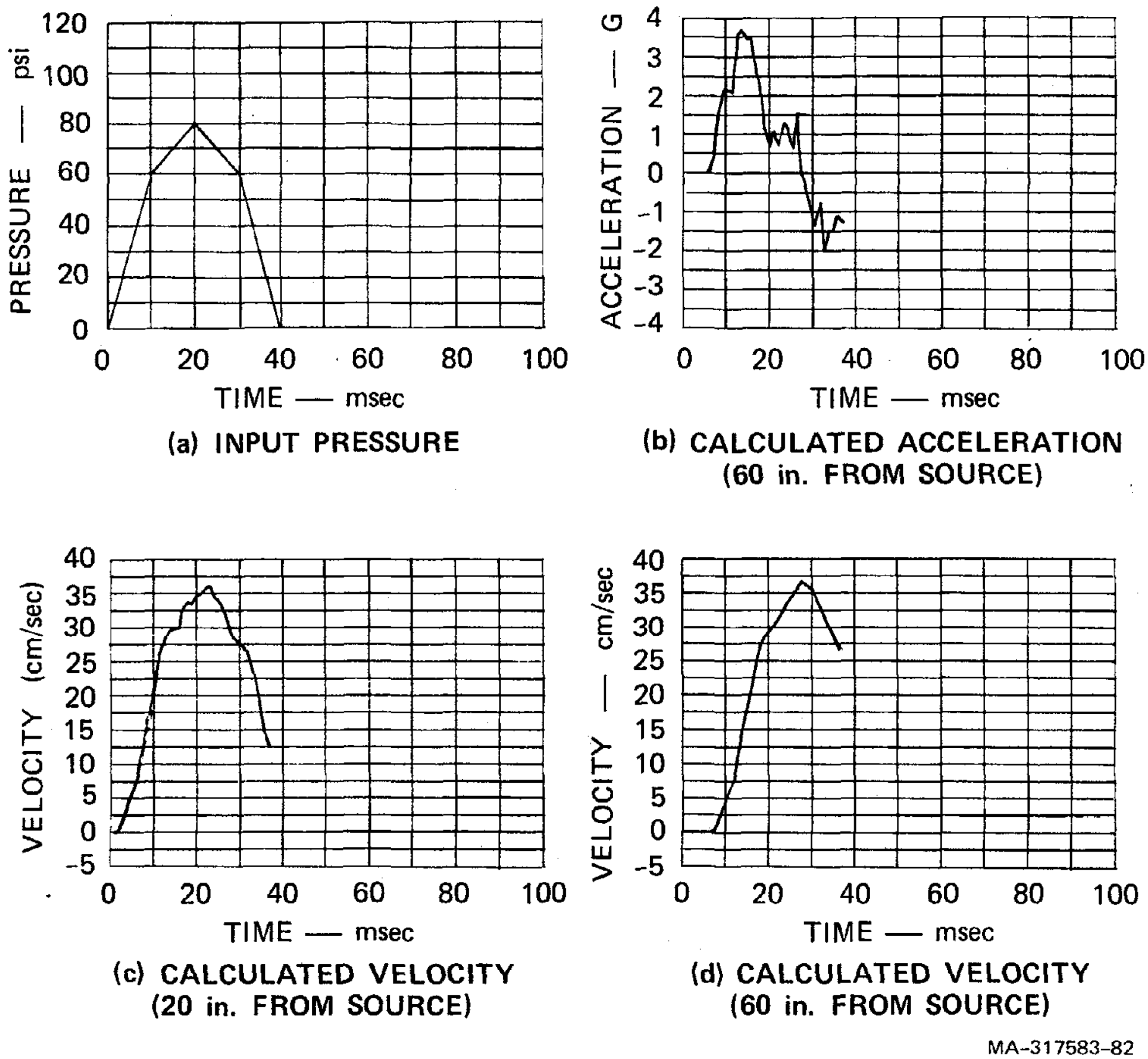


FIGURE 18 CALCULATED ARRAY RESPONSE (NONSAP)

plane wave from 20 in. on out. The acceleration reaches 3.5 g and has a period of 40 ms, corresponding to the specified input. Scaling laws indicate that by increasing source dimensions by a factor of 3, we would obtain a pulse of 1.2 g and a 0.12-s period (8 Hz) in full scale.

V ESTIMATE OF PLANE ARRAY EXPLOSIVE CHARGE WEIGHTS

Reasonable estimates can easily be made for the amount of explosive required to give the desired plane wave free-field motion. Figure 19 shows the features of a representative earthquake accelerogram. The three features most commonly observed are: (1) The envelope of the accelerogram is a curve that rises rapidly to a nearly constant value for a time (about 2 s in Figure 19; this is called the "principal part") and then decays slowly toward zero; (2) total duration of the significant motion is about 10 s; and (3) oscillations within the envelope are random in amplitude and frequency, with central frequencies of the order of 5 Hz. Numerical values of total duration and oscillation frequencies vary from one earthquake to another, but most fall within a decade centered on the values given for the example in Figure 19.

The basic elemental pulse that can be used to build up such oscillograms with a simulation technique is a simple sine wave lasting 1 or 2 cycles. For the example in Figure 19, the period of such elemental pulses should range from about 0.1 to 0.5 s. As shown during the early motion in the figure, the most important period is about 0.2 s. We can envision that a reasonable first approximation of the accelerogram could be made by stringing together a series of 10 elemental pulses, the first 6 with periods near 0.2 s and the remaining 4 with periods near 0.5 s. Some of the desired randomness in amplitude and frequency could be achieved by varying the amplitude of the elemental pulses and by assembling the imperfect sine waves at times not exactly in phase with the pulse periods. Such stringing together of explosive pulses was demonstrated in the UCLA Oak Spring Canyon tests.[1]

Thus, to estimate explosive requirements, we consider the simple sine wave shown in Figure 20. Also shown is a plan view of a row of explosive line sources, Figure 20(a); and an idealization of this row as simply a slit in the earth, Figure 20(b), with an applied internal pressure,

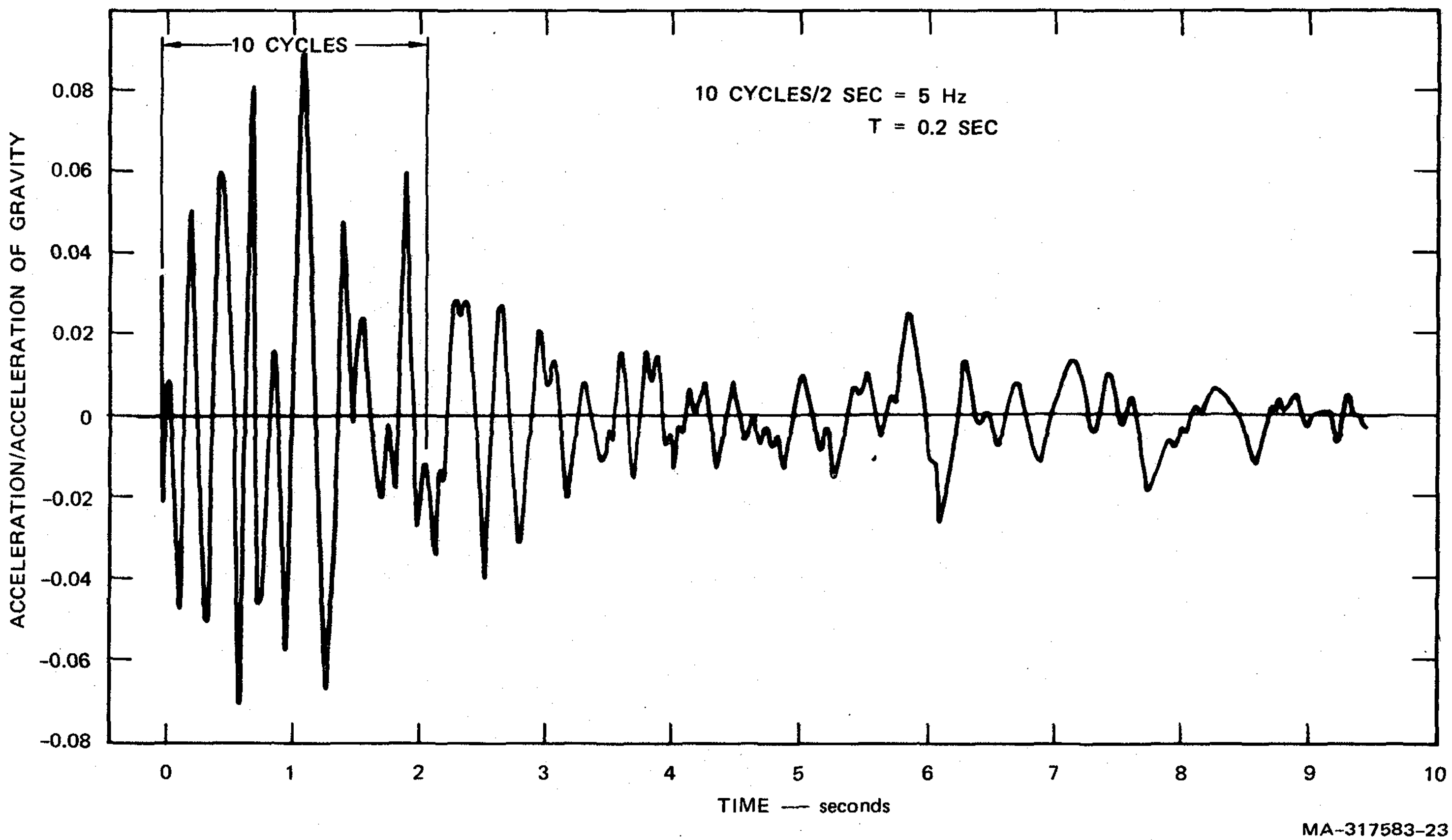
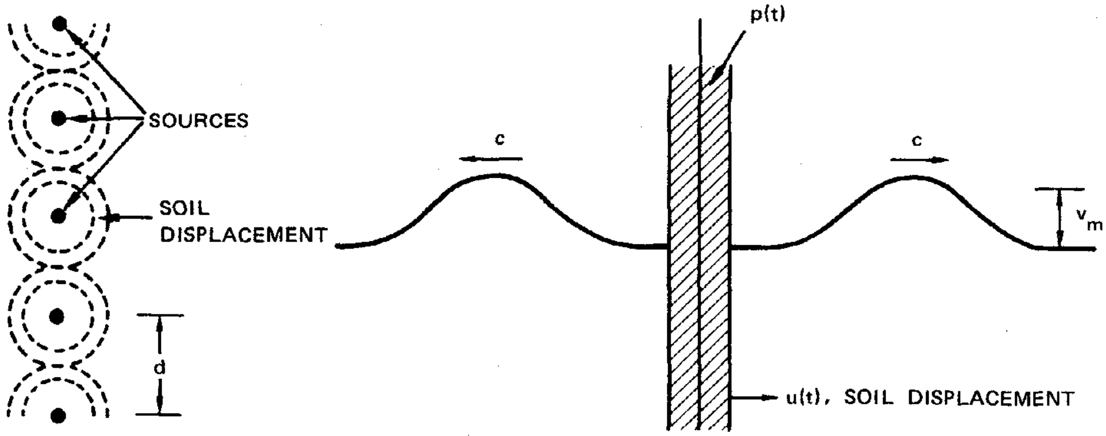
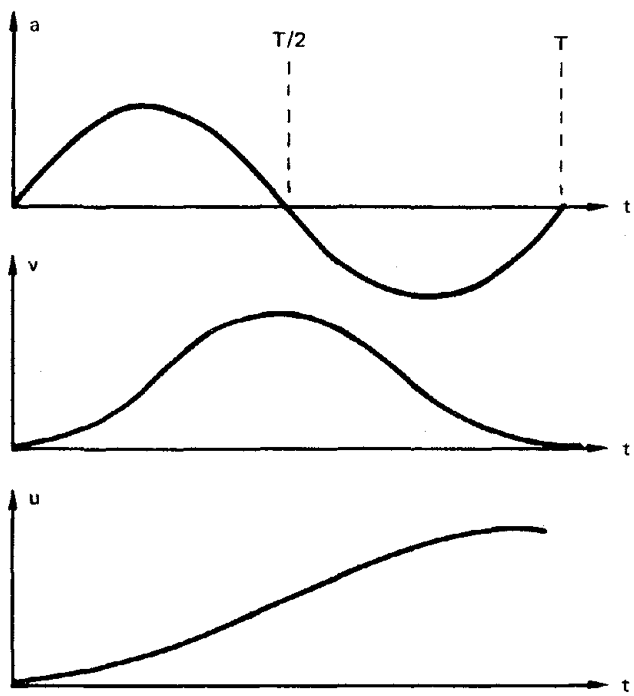


FIGURE 19 ACCELEROGRAM FOR VERNON, CALIFORNIA EARTHQUAKE OF OCTOBER 2, 1933, COMPONENT N 08 E



(a) LINE SOURCE ARRAY

(b) IDEALIZED PLANE SOURCE



$$a(t) = a_o \sin \frac{2\pi t}{T}$$

$$a_m = a_o$$

$$v(t) = \frac{a_o T}{2\pi} \left[1 - \cos \frac{2\pi t}{T} \right]$$

$$v_m = \frac{a_o T}{\pi}$$

$$u(t) = \frac{a_o T}{2\pi} \left[t - \frac{T}{2\pi} \sin \frac{2\pi t}{T} \right]$$

$$u_m = \frac{a_o T^2}{2\pi}$$

$$p(t) = \rho c v(t)$$

$$E = 2 \int_o^{u_m} p(u) du = 2 \rho c \int_o^T v(t) \cdot v(t) dt$$

$$= \frac{3}{4\pi^2} \rho c a_o^2 T^3$$

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FIGURE 20 ONE-DIMENSIONAL IDEALIZATION OF LINE SOURCE ARRAY p(t). For simplicity, we further neglect the influence of the boundaries of the array and of the free surface boundary of the earth so that wave motion can be described by a one-dimensional model with wave velocity c.

The simple sine wave of acceleration, a, is given by

$$a(t) = a_o \sin \frac{2\pi t}{T} \quad , \tag{1}$$

where t is time and T is the period of the wave as indicated in Figure 20. The corresponding particle velocity, v, and displacement, u, from direct integration with zero initial conditions, are

$$v(t) = \frac{a_o T}{2\pi} \left[1 - \cos \frac{2\pi t}{T} \right] \quad , \tag{2}$$

$$u(t) = \frac{a_o T}{2\pi} \left[t - \frac{T}{2\pi} \sin \frac{2\pi t}{T} \right] \quad . \tag{3}$$

The pressure, p, required to produce this wave is given by the one-dimensional wave impedance relation

$$p(t) = \rho c v(t) \quad , \tag{4}$$

where ρ is the material density and ρc is the wave impedance, assumed constant for our purpose.

The mechanical work per unit area, E, done by the pressure p(t) in driving the wave through one period is

$$E = 2 \int_o^{u_m} p(u) du = 2\rho c \int_o^T v(t) \cdot v(t) dt \quad . \tag{5}$$

The first integral is simply the expression for work. The second integral results from a change in the integration variable, du = vdt, and substitution of $p = \rho c v$. Finally, substitution of the prescribed v(t) into the integration yields

$$E = \frac{3}{4\pi^2} \rho c a_o^2 T^3 \qquad (6)$$

To estimate the amount of explosive necessary to provide this flow work, we assume that 1.0% of the 1000 cal/gm chemical energy of PETN is available for work in driving a plane wave.* This value is based on the NONSAP calculation for an array of line sources discussed in Section IV. The input pressure record shown in Figure 18(a) is a realistic pressure pulse that could be expected when 58 gm of PETN is used in a 6-ft source. Using the calculated velocity record given in Figure 18(b), a soil density of 1.85 gm/cm^3, a wave velocity of 0.3 mm/μs (1000 ft/s), and equation (5) above, we calculate the mechanical work done per unit area, E, to be 52 cal/ft^2. Because the array spacing was 2 ft and the depth 6 ft, the total energy coupled is 625 cal or 1.1% of the total available chemical energy of 58,000 cal.

SRI has performed cylinder-piston experiments with expansion times of about 5 ms that show 10% of the chemical energy was recovered in mechanical work. The lower value of 1% found here can be explained through energy lost in expanding the earth around the cylindrical cavities of each line source and through the strain energy held in the rubber bladder. Also, because the desired expansion times here are about 50 ms, more energy is expected to be lost through heat transfer.

For example, the strain energy held in the rubber bladder is 1800 cal when expanded to 100% hoop strain. For a 58-gm charge, this is 3% of the chemical energy. As full-scale sources are designed, the rubber bladder need not have three times the present wall thickness of 0.5 in. (the

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*This is less than the 5% assumed in last year's proposal, but still gives reasonable charge size.

0.5-in. wall thickness is required to prevent tearing of the bladder by the sand that lines the hole). This will lower the percentage of energy held in the full-scale rubber bladder. Better compaction techniques around each source can also lead to more efficient energy coupling. For these reasons we believe that the 1% energy coupling is a lower bound and that 3% to 5% may be possible for future tests.

Using this lower bound of 1% energy conversion and a chemical energy of 1000 cal/gm, we used the energy equation for E to calculate the explosive weights given in Table 1 for a 100 x 30-foot area. Soil density was taken as 1.85 gm/cm^3 and wave velocity as 0.3 mm/μs (1000 ft/s). From Table 1 we observe that to produce an elemental pulse with a period of 0.2 s and an amplitude of 0.1 g, which is typical of those for the early motion in the Vernon earthquake accelerogram in Figure 19, would require only 4 lb of explosive.

Table 1

TOTAL EXPLOSIVE WEIGHTS IN POUNDS FOR A 100 x 30-FOOT ARRAY
(Assuming 1% of chemical energy)

Accel. (g)	Wave Period (s)				
	0.1	0.2	0.5	1.0	2.0
0.1	0.5	4.0	63	505	4,040
0.2	2.0	16.2	253	2,020	16,200
0.5	12.6	101	1,580	12,600	101,000
1.0	50.5	404	6,310	50,500	404,000
2.0	202	1,620	25,240	202,000	1,620,000 (0.8 kt)

However, we would eventually like to simulate much stronger earthquake motions. To produce a 0.5-g amplitude at a 0.2-s period would require 101 lb, which is still quite reasonable. As the peak acceleration and period are increased, the energy in the wave and therefore the explosive weight increase very rapidly to unrealistic values. However, these high wave energies are also unrealistic for actual earthquakes. For this reason, the combinations of high accelerations and long durations are shaded in Table 1. Along parallel diagnols to the left of the shaded area in Table 1, the elemental pulses are more typical of those observed in strong earthquakes. For the most common pulses, explosive weights range from about 10 to 200 lb.

To reproduce a complete accelerogram of the type shown in Figure 19, we can assemble 10 elemental pulses, as given in Table 2. The resulting simulated earthquake would have a peak acceleration of 1 g and a total duration of about 10 s. The required total explosive weight would be about 500 lb. Again, this is a reasonable value for practical use.

Table 2

ELEMENTAL PULSES ASSEMBLED INTO A COMPLETE ACCELEROGRAM

Number of Pulses	Period (sec)	Amplitude (g)	Explosive Weight (lb)
2	0.2	0.5	202
1	0.1	1.0	50
2	0.2	0.2	32
4	0.5	0.1	252
	Total weight:		536

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