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THE DESIGN AND EXECUTION OF THE RAYLEIGH WAVE EXPERIMENTAL PROGRAM AT YUCCA LAKE, NEVADA

A. S. Kusubov

June 22, 1978

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LAWRENCE LIVERMORE LABORATORY
University of California Livermore, California 94550

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PREFACE

The intent of this document is not to summarize experimental results and draw conclusions based on rigorous analysis of test data, but rather to describe field test conditions and the data gathered that might be put to such rigorous analysis. Many assumptions underlying the design of experiments await further confirmation. Accordingly, the author has chosen to supply the type of field-condition detail that might assist further research. For this reason, some of the material in the report is intentionally redundant on the assumption that more, rather than less detail would help recreate the conditions under which the test program was conducted and would provide a guide to the reliability of the data collected. All data are given in the form in which they were gathered: in general, distances and heavy charge weights are given in U.S. customary working units of measure, while times and small charge weights are given in SI units. (A conversion table is provided for convenience.)

Conversion Factors for Changing U.S. Customary Units to the International System of Units (SI) (Symbols of SI units given in parentheses)

To convert from	to	Multiply by
degree (angle)	radian (rad)	1.745 329 E-02
foot	meter (m)	3.048 000 E-01
fps	meters per second (m/s)	3.048 000 E-01
inch	meter (m)	2.540 000 E-02
in. ²	meter ² (m ²)	6.451 600 E-04
in./s	meters per second (m/s)	2.540 000 E-02
kilotons	Joules (J)	4.183 000 E+12
pound (lb avoirdupois)	kilogram (kg)	4.535 924 E-01

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ABSTRACT

Design and field execution of seismic experiments are described that recorded the characteristics of seismic signals from single and multiple explosions conducted at the Nevada Test Site in Yucca Flat, Nevada. Most of the data were obtained from small-scale underground explosions (total yields ranged from a fraction of a pound to 100 lb of explosives) that were designed to permit characterization of seismic signals as a function of explosive-source configuration. Other data were from explosions conducted in the area by others: two underground nuclear detonations with yields below 40 kt each and several surface explosions whose yields ranged from 700 lb to 100 tons. The project included a comprehensive study of the Yucca lake bed, close-range recording of seismic signals from explosions, and excavation of cavities generated by small-scale high-explosive charges.

INTRODUCTION

The experimental data described in this report were collected during a series of tests conducted in 1973-74 and were processed in 1975-76. The data set is a unique collection of seismograms generated by explosions arranged to explore the effects of a variety of basic geometric configurations of emplacement holes. The main objective of the experimental program was twofold: to determine the relative Rayleigh-wave magnitude generated by small-scale explosions at different depths and to study the interaction of Rayleigh waves generated by multiple explosions, examining both as they relate to discrimination between earthquakes and explosions. The program was initiated in conjunction with the Lawrence Livermore Laboratory (LLL) computer-modeling program dealing with Rayleigh-wave generating efficiency related to detecting and determining the magnitude of nuclear explosions. Potentially, this project is of particular interest because of its integrated approach, and because traditionally, experimental and theoretical work on primary waves (P-waves) has taken precedence over work on explosive-generated surface waves (Rayleigh waves, R-waves) because of the difficulty inherent in conducting and interpreting the results of surface-wave experiments.¹ In addition, the need to contain large underground explosions and interest in using explosives to mine and excavate large masses of rock both call for better understanding of the formation of explosive-generated surface waves.

For a number of years the ratio of magnitudes of the R-wave to the P-wave (R/P) (Fig. 1) has been used by the scientific community worldwide to discriminate between earthquakes and explosions. Typically, the R/P ratio for an explosion is much smaller than that for an earthquake². However, the possibility of altering the R/P ratio by programmed firing of several simul-

taneous or sequential charges to disguise explosion-generated seismic signals is a matter of serious concern for those involved in detecting nuclear explosions. Other aspects of detection and identification include discriminating between multiple and single explosions as well as determining the magnitude of explosions.

Understanding ground motions generated by explosions is not limited to detection or magnitude-determination scenarios, alone. If we assume that the magnitude of the Rayleigh wave is directly related to the fracture envelope of the source, an immediate application of the basic understanding of the Rayleigh-wave formation would result in determining the efficiency of underground explosions to fracture rock for fossil-fuel recovery or to fracture coal for *in situ* gasification. In addition, it would help determine the integrity of explosively formed underground storage reservoirs. Other applications of ground-motion study from explosions lie in the areas of reactor siting and bulk storage or transfer facilities of explosive mixtures, such as condensed natural gas and oil byproducts.

To accomplish the program objective and gain an insight into other related problems, some 150 small-scale high-explosive charges with yields ranging from <1-100 lb were detonated in the alluvial deposit of the Yucca Lake at the LLL Nevada Test Site (NTS). Several thousand pounds of high explosives were expended and around 5,000 seismograms were recorded. In addition seismic signals from underground nuclear explosions with yields up to 40 kt and surface explosions with yields up to 100 tons were recorded for scaling and modeling purposes in connection with the Threshold Test Ban Treaty (TTBT) and the Comprehensive Test Ban Treaty (CTBT), as well as other applications of explosive excavation and fracturing.

Fig. 1. Typical seismogram recorded 300 ft from 1-lb surface explosion, and with the definition of R and P magnitudes; (a) unfiltered record and (b) same record filtered by 40-Hz low-pass filter.

For the sake of completeness, every shot has been catalogued and no distinction has been made as to the quality of records, which at this writing still have not been analyzed. A cursory analysis revealed that double-ranging the gain of amplifiers in several instances would have been desirable, since the noise induced by the electrical power generators and tape-drive units was close to the amplitude at the actual P-wave signal. The choice of delays between explosions also could have been improved with due consideration of preliminary results. Unfortunately, however, the field work had to be conducted to meet a very tight budgetary schedule and experiments were performed without the benefit of feedback from shots fired earlier in the series.

The wave-propagation research was complemented by a comprehensive study of the Yucca lake bed and by a seismic source study that consisted of excavating several cavities generated by contained explosions to obtain first-hand information on cavity and crack formation from single and multiple explosions. The preliminary results of this program were reported elsewhere.³

The overall program is best viewed by considering, in turn, the program objectives, the experimental techniques, and, finally, the computational data storage techniques.

Program Objectives

The objective of the Rayleigh Wave Experimental Program was to determine experimentally the ratio of

magnitudes of the R-wave to the P-wave (the R/P), for single and multiple explosions as a function of six factors:

- Depth of burial—effects of single charges detonated at different depths.
- Directional firing—effects of multiple charges detonated in vertical and horizontal arrays simultaneously or with programmed time delays.
- Spatial distribution of charges—effects of multiple charges detonated in vertical and horizontal arrays with various spacings between charges.
- Magnitude of charges.
- Frequency.
- Azimuth.

Experimental Techniques

The field program included five techniques:

- *In situ* geophysical logging and seismic refraction survey of the experimental area to determine the density and sound-velocity distribution of the lake bed.
- Laboratory determination of the physical and chemical properties of the lake-bed to characterize the playa deposit in mineralogical and geological terms.
- Magnetic tape recording of seismic signals from explosions detected by triaxial and uniaxial geophones with natural frequencies ranging between 1 and 4.5 Hz. The geophones were the primary instrumentation for the entire series of experiments.
- Spall measurements with accelerometers to determine the effect of spall on the Rayleigh-wave magnitude.

- Postshot excavation of cavities to gain firsthand information on spall and cavity formation and to determine the difference in crack formation between simultaneous and sequential explosions.

Data Storage Techniques

Three procedures were used to make the seismic data readily available for processing and for comparison with theoretical results:

- Initial data capture was achieved via tape recording in analog form.

- The experimental data were converted from analog to digital form.

- The digitized data were stored on magnetic tapes and in binary microfilm form on photostore in the LLL computer facility.

The tapes serve as master files and offer a direct plotting capability of the digitized data with minimal processing. The data stored on photostore constitute an intermediate file available for in-depth analysis of the seismic signals; they are accessible through the LLL internal timesharing computer network.

EXPERIMENTAL SERIES

The NTS experiments can be divided into two categories. The first consists of experiments fielded by LLL and specifically designed to meet the objectives of the Rayleigh-wave program. These experiments consisted of small-scale underground explosions and are described below. The second category includes nuclear and surface explosions. These explosions were part of experiments unrelated to the Rayleigh-wave program. However, they offered a unique opportunity to extend the data base of the Rayleigh-wave study. They were recorded without interfering with their primary objective.

Site Selection

The playa deposit of Yucca Lake at (NTS)* was chosen to conduct the small-scale high-explosive experiments for two reasons. First, handling high-explosive charges according to federal regulations and the limited availability of support ruled out virtually all available sites but NTS. Second, the playa deposit offered the most uniform deposit at NTS and was believed to be the closest approximation to an ideal half-space. Unfortunately, in the course of our investigations, a previously undetected velocity contrast was discovered at a depth of about 28 ft, complicating data interpretation more than had been anticipated.

Nevada Test Site Geology

The NTS is located within the Great Basin, which consists generally of linear mountain ranges and valleys lying between the Colorado Plateau on the east and the Sierra Nevada range on the west.⁵ The deep basin that

underlies Yucca Flat was formed relatively recently and is mainly of post-Miocene Age. The thick alluvial deposit corresponds to late Tertiary and Quaternary deposits (10-4 million years old). The relative youth of the fault scarps and seismicity indicate that the deep trough underlying the Yucca Flat is still being formed.

The most important Cenozoic structural feature of NTS is a series of north-northwest-trending, predominantly east-dipping faults. From these faults, the centrally located Yucca fault is of particular interest to the current series of experiments because of its proximity to the experimental area. It is the youngest fault of the test site region and was probably formed by a large earthquake. The fault dips at the surface about 75-80°, and extends horizontally for approximately 20 miles in the northerly direction starting at the Yucca lake. There has been no reliable way to date the formation of this fault, its age could be estimated at between 1,000 and 10,000 years from a comparison of its degree of erosion with scarps of known age.

Yucca Lake Bed Geology

Lake beds similar to Yucca Lake are a common feature in the Southwestern Nevada desert and are typically termed "dry lakes." The surface area of the Yucca playa is a little over a square mile, is flat to within a fraction of a foot, yellow in color, and scarred by deep cracks in the Southern end (Fig. 3). Occasionally, in early spring or after a heavy storm, it is a real lake, but less than a foot deep (Fig. 4). Most of the summer it is a dry, hot lake bed providing a relatively uniform firing and diagnostics platform (Fig. 5).

The playa or silt deposit has been deposited by the runoffs from adjacent hills and is a very fine, uniformly compacted and highly impermeable substance. The top of the lake bed is hard enough to be used as a landing strip for larger transport planes. The playa thickness overlying the volcanic tuff and alluvium varies from about 500 feet in the southern end of the lake to 2000 feet in the northern part (Fig. 6).

*The NTS is located in Nye County, Nevada, approximately 60 miles north of Las Vegas. Yucca Lake is bordered by E680 000, N790 000, N810 000, E695 000 and is located roughly in the east central part of the Test Site (Fig. 2). See also Ref. 4.

Fig. 2. Nevada Test Site.

Fig. 3. Map of Yucca Lake showing cracks and detailed topography. Letters identify cracks discussed in text.

Fig. 4. Yucca Lake after a rainstorm.

Fig. 5. Yucca Lake during the dry season. View of diagnostics facility.

The deep cracks in the southern end of the lake are less than 30 years old and, judging from the large quantity of water that flows into them when they are new, they must go to considerable depth. From stress measurements and other estimates it is assumed that the crack spacing is approximately equal to the crack depth. With spacing between cracks ranging from 1,300 feet (between cracks A and B) to 2,200 feet (between cracks C and D), cracks could extend well into the rocks beneath the alluvium (Fig. 6). The depth of the cracks and their regular spacing and orientation with adjacent fault scarps strongly suggest that they are not the well-known shallow polygonal desiccation cracks of desert playas, rather they are of tectonic origin.

Other less prominent, but important features of the lake bed area are expressions of the southern end of the Yucca fault that take the form of two concealed fault lines—one skirting the western shore of the lake and the other cutting across the eastern side of the lake bed (Fig. 6). Erosion has completely destroyed the scarp in this area; observing these fault lines would be rather difficult had they not turned, in places, into drainage ditches.

Yucca Lake Bed Structure

The density of the lake bed obtained by joggling is shown in Fig. 7. For the first 300 ft, it seemed to be

very uniform with a value around 1.7 g/cm^3 . The sound velocity data, on the other hand, show distinctive layering (Fig. 8) and the sonic velocity at the depth of 300 ft has almost double the velocity recorded at the depth of a few tens of feet. The difference between the density and sonic data can be attributed to water saturation of the lower layers since the density measuring tool used is insensitive to water content.*

Seismic refraction survey data are shown schematically in Fig. 9. They consist of the arrival times of the P-wave (longitudinal wave) plotted as function of distance from the explosion and clearly identify an upper layer of the lake bed, confirming the *in situ* sound-velocity measurements. This conclusion is based on the fact that for a medium consisting of a single layer, the P-wave arrival times fit along a straight line with the slope of the line equal to the reciprocal of the sound velocity and with the time intercept going through zero for surface explosions. However, if the medium has a second layer characterized by a higher sound velocity, then such a plot will exhibit a break similar to the one shown in Fig. 9. The slope of the second line characterizing the second layer will be equal to the reciprocal of the second sound velocity and its time intercept will correspond to the depth of the first layer, which can be calculated from Snell's Law.

From the refraction survey we calculate the sound velocity of the first layer to be 1250 fps and for the second layer 2857 fps. The calculated depth of the first layer is about 28 ft which is in good agreement with *in situ* sound velocity measurements.

The "R" lines in Fig. 9 correspond to the Rayleigh-wave velocities. The wave itself exhibits some dispersion because of layering; judging from its velocity (which is about 1200 fps); it appears to be associated with the second layer.

The seismic refraction survey was supplemented by *in situ* shear-velocity measurements with a down-hole geophone and an improvised shear-wave generator consisting of a 6-ft-long 2-by-4 coupled to the ground by the weight of a pickup truck and activated by tapping the end of the 2-by-4 with a sledge hammer. The best available data for the structure of the lake bed is summarized in Table 1.

Petrographical and Chemical Analysis

The optical analysis of the playa samples revealed that the deposit is a clay of submicroscopic size with particle size less than $5 \mu\text{m}$.⁶ The principal minerals are quartz, illite (a clay mineral structurally related to the micas), heulandite and clinoptilolite (zeolites), calcite, and Na-K feldspar. In addition, trace amounts of chlorite (another type of mica) were present. The Na-K

*The downhole logging of density and *in situ* sound velocity measurements were conducted by the Birdwell Division of Seismograph Service Corporation.

Fig. 5. Map of thickness of Yucca Lake deposits of playa and alluvium. Cracks and faults shown are discussed in text.

Fig. 7. Density distribution of Yucca playa, conducted by Birdwell.

Fig. 8. Sonic velocity distribution of Yucca playa, conducted by Birdwell.

Fig. 9. Schematic of the seismic refraction survey of Yucca playa, with the reciprocal of the slope corresponding to the respective wave velocity: P_1 = first-layer sonic velocity (1250 fps); P_2 = second-layer sonic velocity (2857 fps); $R, R_1, R_2, R_3, R_4, R_5$ = Rayleigh-wave velocities corresponding to the trough and crest shown in the detail; Z = first-layer thickness (27.8 ft) = $(T_1 P_1) / 2 \cos[\sin^{-1}(P_1/P_2)]$.

Table 1. Structure of the lake bed deposit

Layer and depth	Longitudinal velocity, fps	Shear velocity, fps	Grain density, g/cm ³
First (0-28 ft)	1250	496	1.3
Second (28-100+ ft)	2870	1140	1.6

Grain density = 3.0 g/cm³, H₂O% ~14%.

feldspar appeared to be a plagioclase, probably a variety of albite.

The x-ray analysis of the playa samples substantiated the optical analysis and showed a medium amount of quartz, illite, K, Na, feldspar, small amounts of heulandite and clinoptilolite and very low amounts (about 5%) of calcite.⁷

The natural state of water content of the core sample varied between 11-14 wt% and the grain density of dried samples was about 3.0 g/cm³.

The water content was determined by establishing the weight difference in core samples after drying for four days at 105°C.⁸ The grain density was determined by helium volumetry in a Beckman Pycnometer on subsamples that had previously been dried for the water content determination and then allowed to return to ambient temperature and humidity. After the grain volume was measured, the samples were redried and weighed so that the grain density of the samples could be calculated without absorbed moisture.

The grain density seemed unusually high for NTS samples, but can probably be accounted for by possible trace amounts of magnetite, which would raise the grain density and which is not easily detected on the x-ray pattern.

On the basis of all the data, the sediment could be called a *mudstone* or *silty claystone*.

Description of Events

The recorded experiments consisted of underground explosions ranging from 1/9 lb (50 g) to 40 kt and surface explosions ranging from 1 lb to 100 tons of high explosive (Fig. 10). The depth of the underground experiments varied from 2 to 50 ft for explosions up to 100 lb and exceeded 1000 ft for kiloton explosions.

Most of the recorded seismic signals were generated by small-scale (≤ 100 lb) underground experiments designed to study the characteristics of the surface and ground motions from underground explosions. These experiments consisted of single and multiple explosions and were grouped for fielding into three experimental series described in the Appendix. Single explosions were designed to determine the effect of the depth of burial on the efficiency of Rayleigh-wave generation and for cross-correlation with multiple explosions, as described below. Multiple explosions consisting of two

to four charges were fired simultaneously or sequentially and were designed to determine the effect of various spacings and delays between explosions arranged in vertical and horizontal arrays. To gain a basic understanding of wave interactions, seismograms from each multiple-explosion array were complemented by a separate set of ground-motion records from experiments in which each explosion of the array was detonated separately. Additionally, seismograms were recorded from single explosions of equivalent weight to the multiple explosions and detonated at depths corresponding to the center of each array. The remaining seismic signals were generated by single nuclear underground detonations and single high-explosive surface detonations conducted by other experimental groups.

In the subsequent paragraphs the events are grouped according to their main experimental objective; the exact location and description of each experiment is given in the Appendix.

Depth-of-Burial Effect

Since the Rayleigh wave is a surface wave, it is postulated that the distance between the explosion and the surface along which the wave propagates play a dominant role in the efficiency of Rayleigh-wave generation.

Rulev⁹ and Vicielli¹⁰ support the conclusion that a maximum in the generating efficiency of the Rayleigh wave exists that is associated with depth. The mechanism of this effect is not understood. Vicielli proposed that the "slap down" caused by spall is the dominant factor. This assumption, however, can be disputed, since Rayleigh waves can also be formed without the "slap down."

To gain a physical understanding of this effect, single charges ranging from 50 g to 100 lb were detonated in emplacement holes from 2 to 50 ft deep. Due to the nature of this investigation, single explosions from every series are represented in this study.

Vertical Arrays

The second series of experiments (Series II) was designed to look at the effect of directional firing in vertical sequences of explosions (Fig. 11). These experiments consisted of detonating three equally spaced 150-g charges arranged in a vertical array with spacings between the charges varying from 8-1 ft, single 150-g charges buried at depths corresponding to each single explosion of the arrays, single 450-g charges buried at depths representing the center of each array and distributed 450-g charges 20 and 16 feet long. The directional firing consisted of detonating the arrays "up," "down," and simultaneous.

For a vertical array consisting of multiple charges, "up" indicates that the charges were detonated sequentially upwards starting with the lowest charge,

Fig. 10. Summary of seismic experiments.

Fig. 11. Vertical arrays: (a) multiple charges; (b) single charge, at a depth equal to the center of the multiple charges; and (c) distributed charge.

"down" means that the upper charge was detonated first, and simultaneous, of course, means that all charges in the array were detonated simultaneously.

Detonating "up" for a distributed charge means initiating the charge at the bottom and letting the detonation move upwards, firing "down" means to detonate the charge at the top.

Due to the proximity of individual charges in the multiple explosion experiments, the maximum delay between the explosions had to be 1.5 times the travel time of the sound wave between the extremities of adjacent charges. This restriction was imposed by the NTS safety requirements to prevent damage or accidental detonation of charges by shock waves from adjacent explosions. Maximum delay between the detonations was 3.6 ms, corresponding to a spacing between the center of charges of 8 ft. Minimum delay between the charges was equal to a fraction of a millisecond, corresponding to a spacing between the center of charges of 1 ft.

Previously published data on vertically distributed charges by Shock,¹¹ Musgrave *et al.*,¹² and Martner *et al.*¹³ are somewhat sketchy and incomplete as far as the seismic net layout and recording of the seismic signals are concerned. There is also no direct comparison to equivalent signal charges detonated at equivalent depths.

Horizontal Array—Linear Arrangement

The effect of directional firing in a horizontal array was studied in Series IIID, which consisted of sequential detonation at a depth of 12 feet of three 1-lb charges separated by about 37 ft. single 3-lb charges, and single 1-lb charges (Fig. 12). In these experiments, a much longer delay could be introduced between the explosions since the charges were located far enough apart to prevent accidental damage or detonation by shock waves generated from adjacent charges. Maximum delay in this series was 200 ms and the minimum delay was 17 ms. The 200-ms delay corresponded approximately to the frequency of the Rayleigh wave and the 17-ms delay to the average frequency of the P-wave.

Fig. 12. Horizontal array, linear arrangement: (a) three 1-lb charges detonated sequentially and simultaneously; and (b) single 1-lb and 3-lb charges.

Horizontal Array—Circular Arrangement

The study of three charges arranged in a horizontal linear array was extended by Series IIIC experiments consisting of detonating at a depth of 12 feet simultaneously four spatially distributed 1-lb charges, single 4-lb charges, and single 1-lb charges. In this series of experiments, a circular charge was approximated by four charges fired simultaneously (Fig. 13). The radius "d" of this quasi-circle was 40 ft for the first set of experiments and 80 ft for the second set. The radii of these circles were chosen to be approximately one-half and one-quarter the wavelength of the Rayleigh wave to have some nominal relation to wave interference.

Fig. 13. Horizontal array, circular arrangement: four 1-lb charges 12 ft deep detonated simultaneously with spacing $d = 40, 80$ ft.

Horizontal Array — Limit of Superposition

Since the underlying principle of all multiple-explosion experiments is the superposition of two or more seismic waves. Series IIB experiments were designed to check the principle of superposition in its simplest form. This was achieved by recording seismic signals from two explosions at the same depth and varying only one parameter—the distance between the explosions. Prior to this series it was postulated that Rayleigh-wave generating efficiency would pass a maximum at some predetermined distance between the charges and that the mechanism for such Rayleigh-wave enhancement could be related to the total elastic damage radius of the source encompassing, both charges in a dipole-related fashion.

The experimental configuration for this series of experiments consisted of simultaneously detonating two single charges at a depth of 50 ft (Fig. 14). The simultaneous explosions were 25 and 50 lb each with spacings between the charges varying from 5 to 100 ft. The single charges were 25, 50, and 100 lb each.

Fig. 14. Horizontal array, limit of superposition: (a) two 25-lb or 50-lb charges detonated simultaneously with spacing d varying from 5 to 100 ft and (b) single 25-, 50-, and 100-lb charges.

Nuclear Explosions

To extend the dynamic range of the small-scale high-explosive experiments and acquire the necessary field experience for design and selection of suitable instrumentation for peaceful nuclear explosions (PNE) monitoring activities associated with TTBT and CTBT, seismic signals from nearby nuclear explosions were recorded without interference with the main purpose of these explosions. The seismic signals were generated by single underground explosions below 40 kt each conducted in the northern part of the Yucca Valley, and were recorded by geophones located on the surface of the Yucca Lake bed. The depths of the explosions were 210 and 466 m respectively.

Surface Explosions

The surface explosions were part of the PRE-MINE THROW IV series of experiments¹⁴ and were conducted for the Defense Nuclear Agency (DNA) by Physics International Co. (PI). The purpose of these explosions was to obtain accurate ground-motion and crater-volume data for high-explosive detonations. The main objective in recording the seismic signals generated by these explosions was to observe the air-blast coupling to the Rayleigh wave as well as to bridge the gap between the small-scale explosive experiments and nuclear explosions. These experiments were conducted on the surface of the Yucca Lake bed and consisted of 0.5, 7.1, and 100.0 tons of high explosive, respectively. As with the nuclear explosions, participation in the surface experiments did not interfere with the main objective of these experiments.

Seismic Line Layout

The seismic lines for most of the small-scale high-explosive underground shots were laid out to observe the formation of the Rayleigh wave as a function of

distance from the explosion and to gain an understanding of the azimuthal propagation of the seismic disturbance (Fig. 15). The spacing between the geophones varied from about 25 ft near the explosion to several hundred feet for geophones located furthest from the seismic source. The maximum length of the seismic line for the small-scale underground high-explosive charges was 2300 ft.

Signals from nuclear explosions were detected by the same geophones as for the small-scale high-explosive experiments, the distance from the nuclear explosions to the nearest geophone was about 16 mi.

For surface explosions, the seismic line extended up to 5000 ft from the explosions and was in line with the main Physics International ground motion line shown in Fig. 35.

The description and exact location of seismic lines with respect to each firing field is given in the Appendix.

High-Explosive Assemblies

The ideal high-explosive source for the seismic wave study would, of course, have been a spherical charge, but the difficult assembly of such charges prompted the substitution of cylindrical charges.

Due to the large number and variety of high-explosive charges involved, plastic explosive Composition C-4 (60% TNT, 40% RDX, with plastic binder) was used for all small-scale underground explosions. The plastic explosive was chosen over the better characterized solid explosive, since charges could then be made by simply packing C-4 into a desired container, rather than machining or pressing the solid explosive.

A typical high-explosive assembly is shown in Fig. 16. Charges up to 4 lb had one detonator and were placed in a cardboard container; charges of 25 lb and over were contained in a sheet metal cylinder and had two detonators as a safety measure.

For most of the charges the length-to-diameter ratio was kept to less than 2. However, for charges of 25 lb and over, it was not economical to bore holes more than 8 in. in diameter, and thus the charges were made into long cylinders. For example, the largest charge weighing 100 lb consisted of a cylinder 8 in. in diameter by 5 ft long.

Initially, standard Reynolds High Voltage RP-1, 1.5 mil bridgewire headers with 1/2-inch tetryl pellet boosters were used to initiate the charges. This assembly, however, proved to have a rather fragile bridgewire for field use and a relatively short shelf life, causing several misfires. The problem was traced to oil from Composition C-4 which would penetrate in several weeks the silastic coating of the tetryl pellet and desensitize the booster.

Fig. 15. Seismic line layout for small-scale underground explosions.

To prevent further misfires, custom-made Reynolds RP-1 boosted detonators were used (Fig. 17). The new Reynolds assembly consisted of a 5-mil exploding bridgewire, initiating low-density PETN, high-density PETN, and high density RDX booster. The assembly was sealed in a brass container to eliminate the possibility of oil penetration from C-4 into the detonator assembly.

The 20- and 16-ft-long distributed charges were manufactured by Explosive Technology, Inc. They consisted of 450 g PETN enclosed in aluminum tubing about 1/2 in. o.d. The charges were initiated by a single Reynolds RP-1 Detonator boosted by a 1/2-in. Tetryl pellet, providing a reliable charge with a long shelf life, since C-4 was not involved in the assembly.

To function as an exploding bridgewire detonator, electrical energy is applied to the bridgewire. The amount of energy has to be great enough to heat the wire to vaporization. Within a few ns after vaporization, the inertia of the wire material is overcome and the wire explodes, giving off a shock wave and the contained thermal energy. In general, the shock wave

from the wire travels about 1500 m/s. As the shock wave travels through the low-density PETN, a detonation is initiated that builds up to approximately 5000 m/s, close to the normal detonation velocity of the low-density explosive. Subsequently, the detonation wave moves into the high-density PETN and the shock wave again increases, due to the higher density of the explosive to about 8000 m/s. The final detonation velocity in PETN has enough energy to detonate the RDX booster explosive, which in turn initiates the Composition C-4 charge. The arrangement of high explosives in a detonator assembly according to their sensitivities and energy release to initiate a larger high-explosive charge is commonly referred to as the "detonation train."

The primary reason for using exploding-bridgewire detonators is their inherent safety characteristics and reliability. Thus, only secondary explosives were used in all parts of the high-explosive assembly, and the high voltage necessary to initiate the explosion prevented accidental detonation.

Fig. 16. High-explosive assembly.

Instrumentation

The electronic equipment necessary to fire the high-explosive charges and to record the ground motion was located in an air-conditioned instrument trailer powered by two diesel generators from a nearby power-generating trailer. The trailer complex also included a portable high-explosive magazine for storage of charges prior to firing (Fig. 5). Postshot excavation of explosive-generated cavities was carried out with a backhoe and handtools.

High-Explosive Firing System

The small-scale high-explosive charges were detonated by exploding the bridgewire within the detonator by a 2.5-kV Capacitor Discharge Unit (CDU; LLL design, specification LE 8283-1B). The main components of the firing system shown in Fig. 18 were located in the instrument trailer and consisted of a trigger unit, delay units to detonate multiple charges, and several

trigger CDU's. To reduce the inductance introduced by the 600-ft-long cables between the instrument trailer and the detonator, a booster CDU for each detonator was placed near the emplacement hole.

The basic components of a CDU are shown in Fig. 19: a 6.5- μ F capacitor, a 96K- Ω charging resistor, a transformer, a three-element spark gap, and peripheral circuits to monitor the charging and discharge cycles. In operation, the capacitor is charged to a desired voltage and the bridgewire is isolated from the high-voltage source by the spark gap. The three-element spark gap consists of two flat plates about 1-3/4 in. in diameter, separated by a gap of 0.055 in. filled with gas. The adjacent side of the gap is connected to the trigger circuit and the opposite to the bridgewire. To fire, a trigger pulse in excess of 1000 V is applied to the trigger circuit, which transforms it to a 5000-V pulse by the transformer. When the boosted trigger pulse is applied to the adjacent plate, it ionizes the gas within the gap, causing the capacitor to discharge, exploding the bridgewire and initiating the detonation train.

Geophones

The main instruments used to detect the ground motion were 4.5- and 1.0-Hz, three-component electromagnetic velocity-sensitive geophones with a nominal response characteristic of 1.5 and 15.0 V/in./s respectively. These are constructed of two coils each wound in opposite directions about a bobbin supported by springs, a centrally located cylindrical magnet rigidly attached to the casing of the geophone, and a cylindrical pole piece to direct the magnetic field perpendicular to the coil windings. When the earth moves, the magnet and its support also move. Because of inertia, the coil tends to remain stationary and lags behind the motion of the earth. The resulting relative motion between the coil and the magnet produces an electromagnetic force across the terminals of the coil that is proportional to the velocity of this motion. Figure 20 schematically illustrates a fixed magnet and a movable coil geophone.

Lead wires
No. 20 AWG copper
6-7 in. long

Fig. 17. Custom-made Reynolds RP-1 exploding-bridgewire detonator: (a) molded header; (b) bridgewire, 5-mil; (c) initiating low-density PETN, 0.25 g; (d) high-density explosive, high-density PETN, 0.365 g; (e) booster explosive, high-density RDX, 3.7 g; and (f) support sleeve, chrome-plated brass, 0.02 in.

Fig. 18. Firing system block diagram.

Fig. 19. Capacitor discharge unit schematic.

Fig. 20. Electromagnetic geophone schematic; coil wound about the bobbin is inertial element; case moves with the earth.

The 4.5-Hz geophones (Fig. 21), manufactured by Mark Products, Inc., were sealed into a waterproof container by the manufacturer and did not require special handling except for grouting in the field with plaster of Paris. The 1.0-Hz geophones (Fig. 22), manufactured by Geo Space Corporation, were mounted in a special bracket for proper alignment (Fig. 23), and then placed into a waterproof container (Fig. 24). Both the bracket and the container were built to LLL specifications. The sealed container was then placed in the ground, leveled, and coupled to the surrounding medium with plaster of Paris (Fig. 25). Each geophone was calibrated *in situ* by recording its natural frequency, the resistance of the coil and the resistance of the damping resistor.

In addition to the above mentioned instruments, a number of other geophones were used to record the ground motions. The exact locations, types of instruments, calibration procedures and specifications of all geophones are given in the Appendix.

Fig. 21. Three-component 4.5-Hz geophone (Mark Products, Inc.).

(a)

(b)

Fig. 22. Geophones: (a) vertical-component unit, 1.0 Hz; (b) horizontal-component unit, 1.0 Hz. (Both Geo Space Corp.)

Fig. 23. Geophone holder and alignment bracket for 1.0-Hz geophones.

Fig. 24. Assembled three-component 1.0-Hz geophone package sealed in a waterproof container.

Fig. 25. Emplacement of three-component 1.0-Hz geophone container.

Accelerometers

To detect the extent of spall caused by the small-scale underground explosions, surface acceleration above the explosion was measured with accelerometers. Since the formation of spall is most readily identified by "free fall," only the vertical component of the acceleration was recorded. The instruments used to record the spall were "force balance" servo units—Kistler Model 305A. The accelerometers were placed 2 to 12 ft from the emplacement holes and were mounted on 6-in.-long, 1-1/2-in.-by-1-1/2-in. wooden pegs driven flush into the ground.

The components of the accelerometer shown in Fig. 26 are the seismic mass consisting of a space-wound forcer coil and a capacitor plate, a truncated conical permanent magnet with a pole piece, a capacitive displacement sensor, and an amplifier. The seismic mass is supported by six flexures arms (Fig. 27) forming three dynamic parallelograms that have purely translational motion along the axis of the casing. The pole piece directs the magnetic field perpendicular to the windings of the forcer coil.

In operation, the seismic mass is minutely displaced with respect to the casing when the unit is subjected to acceleration. The displacement unit detects the movement of the mass relative to the case. The amplifier converts this displacement signal into an electrical current which is fed into the forcer coil located in the permanent magnetic field generating a proportional force that is applied to the seismic mass. In this manner, the spatial separation between the seismic mass and the displacement sensor is held constant by balancing the force created by acceleration against the electronically generated restoring force. Since the restoring force is proportional to the acceleration, the electrical output signal of the servo accelerometer is also proportional to the acceleration.

Data Recording

The signals from the geophones were amplified in the diagnostics trailer, converted from voltage to frequency records by Voltage-Controlled Oscillators (VCO's), and then recorded in the analog form several geophone signals per tape track (Fig. 28). This condensed form allowed up to four geophone records per tape track. The analog tapes recorded in the field were digitized in Livermore, where the reverse process took place: the condensed data were read with discriminators corresponding to the carrier frequencies of the VCO's, converted to digital form, and recorded on magnetic tape. Subsequently, the digital data stored on tapes were processed by a Control Data Corporation (CDC) 7600 computer and stored on photostore, providing an easy access for analysis and data handling.

The signals generated by the accelerometers were displayed directly on oscilloscopes in the instrument trailer and recorded on Polaroid film.

Cavity Excavation

The seismic records were complemented by excavation of several selected cavities from Series II and IIIA. First a 3-ft-wide trench was dug with a backhoe along the row of the emplacement holes to a depth of several feet below the cavity location without exposing the cavity (Fig. 29). Then the cavities were carefully opened with handtools, cleaned, and photographed. Figure 30 shows an excavated cavity generated by 150 g of high explosive buried 4 ft deep. The soot and smoke

Fig. 26. Schematic of "force balance" servo accelerometer.

Fig. 27. Accelerometer assembly.

Fig. 28. Schematic of field-recording and LLL-digitizing operations.

Fig. 29. Excavation of cavities.

Fig. 30. Excavated cavity generated by 150 g Composition C-4 buried 4 ft deep (cavity diameter = ~10 in.).

Fig. 31. Detail of cavity shown in Fig. 30.

Fig. 32. Vertical cracks of excavated cavity.

generated during the explosion served as an excellent marker for outlining cracks formed during and immediately after the explosion. The record shows the well-developed radial cracks radiating from the center of the cavity at an angle of 45° with respect to the horizontal and rectangular cracking of the cavity walls. A close-up of the same cavity is shown in Fig. 31.

A view of a cavity excavated to show the cracks along the vertical plane is given in Fig. 32. Excavated cavities generated by a simultaneous explosion of three charges of 50 g each are shown in Fig. 33.

Fig. 33. Excavated cavities generated by three simultaneous explosions of Composition C-4, 50 g each, with depths of 4, 5, and 6 ft, respectively (cavity diameter = ~7 in.).

Data Storage

In organizing the entire data base of some 5000 seismograms, special care was taken to identify the experiment each seismic record was part of. To achieve this, each record was labelled by its series number, shot number, units the data is represented in, location of the recording geophone and axis of the recorded ground motion. For example, the seismogram AK2, SHOT 1, BITS, 100VS refers to Series 2, Shot 1, bit format, geophone location 100 ft south from the explosion, vertical axis.

For direct access to the data for plotting, processing and viewing of the seismograms on a visual display unit—TMDS, the entire data set was digitized and then stored on magnetic tapes and on the LLL photostore.

Analog-to-Digital Conversion

The seismic field data recorded in analog form at NTS were digitized at LLL by the program-controlled EMR data-handling system composed of an EMR 6130 computer, an EMR telemetry console, and other peripheral equipment. This system can handle data rates of 750,000 8-bit data bytes per second in 27-ms segments. The typical sampling rate for digitizing was 10 kHz with 12,288 bits from bandedge to bandedge.

The digitized data were first stored on a 7-track digital tape using a routine called BABY¹⁵, viewed for

verification via a CRT with the BBYPLOT¹⁶ routine, and printed on the Line Printer with the CPLT¹⁷ routine. Since a baseline shift was incurred due to the center-frequency variation, every seismic record or file was normalized with the BBCAL¹⁸ routine to the baseline recorded several seconds prior to zero time.

Photostore

The digitized data were stored on photostore with LLL subroutines ELF¹⁹ and ADCFLS²⁰, in the SOCKITTOME²¹ format, making them available for processing and plotting by this convenient, conversational code. To facilitate the location of a desired seismogram, the data were stored in the available photostore directory format. To protect the original data, TAKE files were created that permit users to access data but prevent them from writing over the original files.

The entire data set is stored under the YUCCA directory with other subdirectories referring to the actual identification of the series, the shot number, units, and finally the files themselves, identified by the geophone location and the direction of the recorded ground motion. The LLL subroutine LST¹⁰ (Fig. 34) can be used to quickly locate the necessary file in the computer storage by entering the main directory YUCCA and subsequently opening the desired subdirectories from the listing provided.

ELF / 22

• LST • R:YUCCA

DM• P0 AK1

DM• P0 AK2

DM• P0 AK3

DM• P0 MINE THROW

DM• P0 NUCLEAR

LST

• LST • R:YUCCA:AK2

• LST • R:YUCCA:AK1

.....

DM• P0 SHOT1

DM• P0 SHOT2

DM• P0 SHOT3

DM• P0 SHOT4

DM• P0 SHOT5

DM• P0 SHOT6

LST

• LST • R:YUCCA:AK2:SHOT1

• LST • R:YUCCA:SHOT1

.....

DM• P0 BITS

DM• P0 MB

DM• P0 MS

DM• P0 RR

LST

• LST R:YUCCA:AK2:SHOT1:BITS • LST • R:YUCCA:AK1:SHOT1:MB •••

FL• P1 025VS

FL• P1 075VS

FL• P1 100LS

FL• P1 100TS

FL• P1 100VS

FL• P1 133VS

FL• P1 166VS

FL• P1 200LS

FL• P1 200TS

FL• P1 200VS

FL• P1 250VS

FL• P1 300LS

FL• P1 300TS

FL• P1 300VS

FL• P1 350VS

FL• P1 400LS

FL• P1 400TS

FL• P1 400VS

FL• P1 450VS

LST

ALL DONE

•BYE

Fig. 34. Call routine for locating seismic records maintained on photostore.

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APPENDIX

Selection of the Seismic Fields

In selecting a suitable seismic field for each series of experiments on the surface of the Yucca Lake, three major constraints had to be taken into consideration.

The most obvious interference with the propagation of seismic signals would, of course, arise from the deep cracks at the southern end of the Yucca Lake. Second, the ongoing Physics International experiments required that the LLL instrumentation trailers be at least 4000 ft away from Event No. 6, 1000-ton surface shot, due to the expected overpressure from the explosion. The last major constraint, although not readily visible, was the southern end of the Yucca fault cutting across the lake bed. Care was taken to locate the seismic fields at a safe distance to minimize the influence of the expected interference. However, in the case where more than one seismic line was used, several geophones had to be located very close to the fault line.

The location of the seismic fields is shown in Figs. 35-37.

Shot Description and Layout

A description of each LLL-fielded experiment is provided in the paragraphs that follow. Since the fielding of nuclear and surface explosions was the responsibility of other experiment groups, only information directly pertinent to the recording of seismic signals is given.

Once the field for a particular LLL series of experiments was selected, care was exercised to minimize the interference between experiments by providing adequate spacing between emplacement holes and fire shots in an order that eliminated the passage of the seismic disturbance through a zone already rubblelized by previous explosions. To facilitate the comparison between experiments, all shots of a particular series of experiments were placed above or below the 28-ft velocity contrast.

The emplacement holes varied between 2 to 8 in. in diameter. The 2-in.-diameter holes were used for the smallest explosions, 4-in.-diameter holes for the intermediate, and the 8-in.-diameter holes for the largest high-explosive charges. The choice of diameters was

partially influenced by the desire to maintain the length-to-diameter ratio of charges as close to 2 as practical.

The 2-in.-diameter explosions were stemmed only with plaster of Paris. The other shots were stemmed with alternating layers of Monterey sand and magnetite sand to attenuate the shock wave in the emplacement holes; they were capped with a plaster of Paris plug.

All explosive charges were lowered by hand into the emplacement holes with a nylon rope.

Series I

This first series of experiments consisted of explosions from 50-450 g, and was mainly a shakedown series designed to check the firing and diagnostics systems, to develop a suitable high-explosive charge, and to answer a number of other questions associated with the field work. Figure 36 and Table 2 give the location and description of these experiments.

Series II

The main objective of Series II experiments consisting of explosions from 150-450g was to determine the depth of burial effect and compare the Rayleigh-wave generating efficiency between single and multiple explosions arranged in a vertical array. The geophones for this series were also laid out to obtain a detailed seismic survey of the lake bed that included reverse firing. (Figs. 38-40).

For sequential detonations in the downward direction, the explosive charges could not be placed into a single emplacement hole since the upper charge, which would be detonated first, would have destroyed the firing cables of the lower charges. The bore-hole configuration for those experiments consisted of three separate emplacement holes—the upper charge was placed in a vertical hole and the lower two charges into emplacement holes drilled at an angle of 30° with the vertical and offset radially with respect to each other to minimize communication during the drilling operation (Fig. 41).

The description of this series is summarized in Table 3.

Fig. 35. Location of seismic experiments.

Legend:

L-15 — 4.5-Hz, 1.5-V/in./s, three-component geophone

HS-10-1—1.0 Hz, 15.0-V/in./s, vertical-component geophone

● — Geophone location and corresponding distance in feet from the firing field reference line

○ — Emplacement hole location and corresponding shot No.

Fig. 36. Series I seismic field layout.

Table 2. Series I shot description

Shot No.	No. charges	Weight each charge, g	Depth of a burial, ^a in.	Detonation configuration	Delay between detonations ms
1	1	150	55	—	—
2	1	300	55	—	—
3	1	450	55	—	—
4	1	150	29	—	—
5	1	300	33	—	—
6	1	450	28	—	—
7	3	50	40.5, 55.5, 70.5	Simultaneous	—
8	—	—	—	—	—
9	3	50	40.5, 55.5, 70.5	Sequential "up"	0.5
10	3	50	41.5, 55.5, 69.5	Sequential "up"	0.3

^aCenter of charge

Fig. 37. Series II and III seismic field layout.

Legend:

- — Vertical emplacement hole location and corresponding shot No.
 □ — 30° emplacement hole. (See Fig. 41)

Fig. 38. Series II firing field layout.

Legend:

- HS-1 — 4.5-Hz, 0.5-V/in./s, vertical-component geophone
 HS-10 — 2.0 Hz, 3.0 V/in./s, vertical-component geophone
 HS-10-1 — 1.0 Hz, 15.0-V/in./s, vertical-component geophone
 L-15 — 4.5-Hz, 1.5-V/in./s, three-component geophone
 ● — Geophone location, and corresponding distance in feet from the firing field
 Reference line — South
 ○ — Emplacement hole location and corresponding shot No.

Fig. 39. Series II South seismic line layout and reverse firing field, South.

Legend:

HS-1 — 4.5-Hz, 0.5-V/in./s, vertical-component geophone

HS-10 — 2.0 Hz, 3.0-V/in./s, vertical-component geophone

HS-10-1 — 1.0 Hz 15.0-vertical-component geophone

● Geophone location and corresponding distance in feet from the firing field
Reference line North

○ Emplacement hole location and corresponding shot No.

Fig. 40. Series II North seismic line layout and reverse firing field, North.

Shot No. 18

Shot No. 19

Shot No. 20

Shot No. 21

Fig. 41. Series II emplacement holes for sequential "down" detonations.

Table 3. Series II shot description

Shot No.	No. charges	Weight each charge, g	Depth of burial, ^a ft	Detonation configuration	Delay between detonations ms
1	1	450	19	—	—
2	1	450	19	—	—
3	1	450	19	—	—
4	1	450	19	—	—
5	1	450	17.33	—	—
6	1	450	16	—	—
7	1	450	12	—	—
8	1	450	8	—	—
9	1	450	4	—	—
10	3	150	20, 19, 18	Simultaneous	—
11-E	3	150	20, 18, 16	Simultaneous	—
12	3	150	20, 16, 12	Simultaneous	—
13	3	150	20, 12, 4	Simultaneous	—
14	3	150	20, 19, 18	Sequential "up"	0.3
15	3	150	20, 18, 16	Sequential "up"	0.7
16	3	150	20, 16, 12	Sequential "up"	1.8
17	3	150	20, 12, 4	Sequential "up"	3.6
18-25	1	150	12	—	—
19	3	150	20, 18, 16	Sequential "down"	1.0
20	3	150	20, 16, 12	Sequential "down"	1.8
21	3	150	20, 12, 4	Sequential "down"	3.6
22	1	150	19	—	—
23	1	150	17	—	—
24	1	150	16	—	—
25	2	150	12, 8	—	—
26	1	150	8	—	—
27	1	150	4	—	—
28	1	150	20	—	—
29	1	450	2	16-ft-long distributed charge "up"	—
30	1	450	2	16-ft-long distributed charge "down"	—
31	1	450	2	20-ft-long distributed charge "up"	—
32	1	450	2	20-ft-long distributed charge "up"	—
500S	1	450	20	—	—
501S	1	450	23	—	—
A	1	450	19	—	—
E	1	450	2	20-ft-long distributed charge "up"	—
G-1	1	150	15	—	—
H	1	150	15	—	—
I	1	150	14.33	—	—
J-1	1	450	15	—	—
J-2	1	450	4	—	—
N	1	450	15	—	—
O-1	1	450	15	—	—
O-2	1	150	10	—	—
O-3	1	150	5	—	—
P-1	1	900	30	—	—
P-2	1	450	25	—	—
P-3	1	450	12	—	—
R	1	150	2	—	—

^aBottom of charge

Series III

The third series of small-scale high-explosive experiments consisted of four parts—A, B, C and D, with parts B, C, D grouped in a single seismic field (Fig. 37, 42). The main objective of this series of experiments (parts B, C, and D) was to compare the Rayleigh-wave generating efficiency between single and multiple explosions arranged in a horizontal array.

Part A was designed to complement results of Series I and consisted of single and multiple explosions less than 1 lb. This series of experiments was also laid out to facilitate the excavation of cavities after explosions (Fig. 43, Table 4).

Part B consisted of 25- and 50-lb charges detonated in pairs at varying distances (Fig. 44, Table 5).

Part C was a minimal approximation for a horizontal circular charge consisting of four 1-lb charges detonated simultaneously (Fig. 45, Table 6).

Part D consisted of 1-lb charges arranged into a linear horizontal array with three explosions detonated at varying delays (Fig. 46, Table 7).

The seismic line layout for these experiments is summarized in Fig. 47.

Nuclear Explosions

The recording of seismic signals from nuclear explosions in the kiloton range was mainly performed for scaling purposes and PNE applications. The seismic line for these explosions was the same as for Series II experiments, thus providing an opportunity to study the response of readily available geophones relatively close to a nuclear explosion. Figure 48 summarizes the locations and types of geophones used in this series of experiments.

Surface Explosions

Recording the seismic signals from surface explosions of up to 100 tons of explosives had two purposes: scaling and observation of the response of geophones to air blast. Events 2 and 3 were among the first large-scale explosions to be recorded on the magnetic tape and, along with Series I, were part of the shakedown experiments. It was also in this series of experiments that the grouting of the triaxial 1-Hz geophones was perfected. The location of these explosions their magnitude and their seismic line are shown in Fig. 49.

Fig. 42. Series III B, C, and D firing field layout.

Legend:

HS-1 — 4.5-Hz, 0.5-V/in./s, vertical-component geophone

HS-10 — 2.0 Hz, 3.0 V/in./s, vertical-component geophone

HS-10-1 — 1.0-Hz, 15.0-V/in./s, vertical component geophone

- Geophone location and corresponding distance in feet from the firing field reference line.
- Emplacement hole location and corresponding shot No.

Fig. 43. Series III A seismic field layout.

Table 4. Series III A, shot description

Shot No.	No. charges	Weight each charge, g	Depth of burial, ^a ft	Detonation configuration	Delay between detonations ms
1	3	50	6, 4, 2	Sequential, "up"	0.75
2	3	50	6, 4, 2	Simultaneous	—
3	1	50	6	—	—
4	1	50	5	—	—
5	3	50	6, 5, 4	Simultaneous	—
6	3	50	6, 5, 4	Sequential, "up"	0.3
7	3	100	6, 4, 6, 3, 2	Simultaneous	—
8	1	150	5	—	—
9	1	150	5	—	—
10	1	50	2	—	—
11	—	—	—	—	—
12	1	150	4	—	—
13	1	450	6	—	—
14	1	50	4	—	—
15-1	1	50	6	—	—
15-2	1	50	1	—	—
16	1	150	4.6	—	—
17	1	450	2	—	—
18	1	150	2	—	—
19	—	—	—	—	—
20	1	50	1	—	—
21	1	50	1.3	—	—

^aCenter of charge

Fig. 44. Series III B firing field layout.

Table 5. Series III B shot description

Shot No.	No. charges	Weight each charge, lb	Depth of burial,* ft	Horizontal spacing, ft	Detonation configuration
1	1	25	50	—	—
2	1	25	50	—	—
3	1	50	50	—	—
4/5	2	25	50	50	Simultaneous
6	1	50	50	—	—
7/8	2	50	50	25	Simultaneous
9/10	2	25	50	25	Simultaneous
11	1	50	50	—	—
12	1	50	50	—	—
13/14	2	50	50	10	Simultaneous
15/16	2	25	50	100	Simultaneous
17/18	2	50	50	5	Simultaneous
19/22	2	50	50	100	Simultaneous
20/21	2	25	50	10	Simultaneous
23	2	25	50, 46	4-ft vert spacing	Simultaneous
24	1	25	50	—	—
25/26	2	25	50	5	Simultaneous
27	1	100	50	—	—
28	1	50	50	—	—
29	1	100	50	—	—
30	1	50	50	—	—
31	1	25	50	—	—
32	1	50	50	—	—

*Center of charge

Fig. 46. Series III D firing field layout.

Table 7. Series III D, shot description

Shot No. ^a	No. charges	Weight each charge, lb	Depth of burial, ^b ft	Horizontal spacing, ft	Detonation configuration ^a	Delay between detonations ms
1	—	—	—	—	disposal hole	—
8/5/2	3	1	12	37.5, 37.5	sequential	50
3	1	1	12	—	—	—
10/7/4	3	1	12	37.5, 37.5	sequential	150
6	1	1	12	—	—	—
15/12/9	3	1	12	37.5, 37.5	sequential	100
11	1	1	12	—	—	—
13	1	1	12	—	—	—
14	1	3	12	—	—	—
16/19/23	3	1	12	37.5, 50.0	sequential	17
17/20/24	3	1	12	37.5, 50.0	sequential	200
18/21/25	3	1	12	37.5, 50.0	simultaneous	—
22	1	3	12	—	—	—
26	1	1	12	—	—	—
27	1	3	12	—	—	—
28	1	3	12	—	—	—
29-1	1 ^c	1	30	—	—	—
29-2	1 ^c	1	30	—	—	—
29-3	1 ^c	1	30	—	—	—
29-4	1 ^d	1	30	—	—	—
29-5	1 ^d	1	25	—	—	—
29-6	1 ^c	1	20	—	—	—
29-7	1 ^c	1	18	—	—	—
29-8	1 ^d	1	18	—	—	—

^aEmplacement hole order indicates the firing sequence

^bNo^c stemmed.

^cCenter of charge

^dStemmed.

Legend:

● Geophone location

HS-10 – 2.0-Hz, 3.0-V/in./s, vertical component geophone

HS-10-1 – 1.0-Hz, 15.0-V/in./s, three-component geophone

HS-10-1* – 1.0-Hz geophone 41.0-V/in./s, Vertical- and radial-components
15.0-V/in./s, Transverse-component

L-15 – 4.5-Hz, 1.5-V/in./s, three-component geophone

L-1E* – 4.5-Hz, 4.0-V/in./s, three-component geophone

L-4C – 1.0-Hz, 11.0 V/in./s, three-component geophone

Fig. 47. Series III B, C, and D seismic line layout.

Legend:

- Geophone location with corresponding distance in feet from the Series II firing field reference lines, north or south, respectively.
- HS-1 - 4.5-Hz, 0.5-V/in./s, vertical-component geophone
- HS-10 - 2.0 Hz, 3.0 V/in./s, vertical-component geophone
- HS-10-1 - 1.0 Hz, 15.0-V/in./s, vertical-component geophone
- L-15 - 4.5-Hz, 1.5-V/in./s, three-component geophone

Fig. 48. Nuclear explosion seismic line layout.

Legend:

- Geophone location with corresponding distance in feet for Event No. 6
- Surface explosion location and corresponding event number
- HS-10-1* - 1.0-Hz, 15.0-V/in./s, vertical component geophone
- HS-10-1 - 1.0-Hz, 15.0-V/in./s, three component geophone

Fig. 49. Surface explosion seismic field layout and shot description. Event No. 2—0.5 tons, Event No. 3—7.1 tons, Event No. 6—100 tons.

Firing System of the Small-Scale High-Explosive Charges and the Data Acquisition²²

The following information was compiled to illustrate the specifics of the electronics system from the users' point of view along with recommendations for the next generation of firing and data acquisition systems.

Firing System Description

Figure 50 is a block diagram of the existing firing system. The 2.5-kV charging power supply is a CDU with the head removed. The firing currents are monitored for each shot by measuring the voltage across a 0.05 ohm CVR (current viewing resistor) and displaying the voltage on an oscilloscope. The oscilloscope is calibrated at 20 V/cm. Each cm represents 20 V/0.05 Ω or 400 A. The firing voltage is a measure of the charging voltage and is displayed on a meter and/or recorded on a strip chart recorder through a 100:1 divider. The firing system is test-fired just prior to each live detonation. In the event of a malfunction in the test firing, or a misfire, the monitors will usually show the reason for the malfunction. With the present system, it is possible to fire four charges simultaneously or sequentially and monitor each CDU. In addition, it is also possible to display zero time and two of four current monitors on a single scope in order to verify detonation times in sequential firings. Firing of the charges is done usually by an electronic technician who has been checked out in high-explosive detonation procedures. During the audible countdown by the technician, which starts ap-

proximately 5 s before zero time, the visicorder is started approximately 3 s before zero time, the camera shutters are opened at approximately 2 s before zero time and the shot is fired at zero time. Approximately 2 s after zero time, the camera shutters are closed. The magnetic tape recorder is started at about 30 s before zero time and stopped approximately 60 s after the explosion.

Data Acquisition

Figure 51 shows the existing data acquisition system. Data from the geophones are amplified (with settable gains of 1 through 1000) by the differential amplifiers. The amplifier outputs are attached to the VCO inputs. Groups of 4 VCO's are then multiplexed and recorded on one track of the magnetic tape recorder. There are 12 tracks available for data recording, which allows for 48 geophone inputs. Track 13 is normally used for recording time from the time code generator. Track 14 records zero time through a 2.3-kHz VCO from the output of the zero time scope. After each shot, it is possible to play back the tape recorded data. However, with the present system, it is necessary to make 48 passes of the data, due to lack of the necessary tape recorder output equipment and a suitable chart recorder.

In the present system, 24 amplifier outputs can be patched into two 13-channel visicorders through galvanometer-driver amplifiers. Channel 13 of each visicorder is reserved for recording zero time.

Fig. 50. Firing system.

Fig. 51. Data recording system.

Recommendations

A number of improvements, as outlined below, can be made to the existing system that will allow for more efficient operation and produce better data.

- Installation of a variable-delay sequence timer would allow one operator to run the entire system. The sequence timer could remotely operate the equipment as follows:

The tape recorder would always be started at the same time before zero time. This would allow a uniform time between shots which could help in data reduction in that the operator at the data reduction center would know exactly where data from a particular shot could be found.

The visicorders could be started at some predetermined time after the tape recorders by setting the proper time in the sequencer.

The monitor camera shutters could open at some preset time before zero time, and close at some time after zero time. The time would always be the same and would produce uniform exposures. In the past, exposure time varied and in some instances the pictures were very poor.

After the camera shutter is opened, a firing pulse would be sent to the CDU trigger (The zero time monitor for the tape recorder and visicorder could originate in the sequencer.)

The visicorder could be stopped at a time after the data has been collected.

The tape recorder would then stop automatically.

The sequencer would eliminate the need for an oscilloscope to produce a zero time pulse.

- A four-channel variable-delay-trigger generator would produce four CDU trigger pulses at 4 preset times for sequential firings. The chassis would take up about 5 in. of rack space instead of the present 24 in. The monitor scopes would function as monitors only

and not as delay generators for sequential firing. The oscilloscopes must be reset before every shot and, if the operator forgets to reset the scopes, the 2nd, 3rd, etc. detonations would not occur. Transients have triggered the scopes at various times also. The trigger generator could be designed such that it would not respond to transients.

- Currently, the VCO's used in Trailer 81 are LLL-designed and are extremely temperature-sensitive. The minimum time required for stabilization of the center frequency is approximately 2 hours. The VCO's could be replaced with commercial VCO's with a maximum stabilization time of 15 minutes. The commercial VCO's would take about half the space of the LLL-designed VCO's.

- If it is necessary to review shot data in the field, a system capable of playing back the 48 channels of data from the tape recorder in 6 to 8 passes would save a great deal of time. Playback time now is 35 to 45 minutes for 48 channels; it is tedious and prone to errors.

- Another possible improvement for the diagnostics system would be a digital data recording system. The main advantages would lie in obtaining data over a much wider range of amplifications and in data reduction. The output from the tape recorder could be computer-compatible, to eliminate the need for digitizing. Digitizing analog data is both expensive and time-consuming.

Conclusions

System reliability and data quality were very good over the entire program. We lost probably no more than 1 or 2% of the data out of the thousands of individual signals recorded. The instrumentation methods provided the necessary information to support the small-scale high-explosive experiments.

Geophone Calibration

To obtain a more accurate ground motion value, most of the geophones, in addition to a thorough calibration in the laboratory before the experiments, were calibrated *in situ* (i.e., a method was used to calibrate geophones after they had been grouted into the ground). The devised scheme consisted of measuring the natural frequency and the total resistance for each geophone using the same transmission cables and damping resistors employed to record the seismic signals during the experiments. This method accounted for any differences between the laboratory calibration values and the response of the geophones during the experiments. The natural frequency was measured by the phase-resonance method based on Geo Space Corp. recommendations; the equipment consisted of an oscilloscope, a low-frequency oscillator, and a digital frequency meter. (See Fig. 52.)

Fig. 52. Geophone calibration schematic (R should be 10 times the coil resistance of the geophone, at a minimum).

The equipment configuration shown in Fig. 52 forms a Lissajous pattern on the oscilloscope. By adjusting the oscillator frequency in a range near the natural frequency of the geophone, the Lissajous pattern can be made to close. Since the voltage across the resistor is always in phase with the current, the pattern will close

only when the current through the geophone is in phase with the voltage.

When the frequency of the oscillator is below the natural frequency of the geophone, the current through the geophone lags the voltage. When the natural frequency is higher, the current leads the voltage. Only at its natural frequency does the geophone become a unity power factor load. Therefore, when the pattern closes, the oscillator frequency represents the natural frequency of the geophone. This method does not consider the effect of the inductance of the coil winding, which is negligible.

In practice, it was observed that the natural frequency of the instruments will change after it has been transported into the field and grouted. The changes were usually associated with the geophone not being quite level after grouting, resulting in higher natural frequencies. The geophones with lowest natural frequencies were affected the most and changes up to 1 Hz were observed on several occasions.

Frequency Response Curves and Specifications

The specifications of geophones and accelerometers used to record seismic signals are listed in Tables 8-14 and Figs. 53-60. The frequency response curves shown in Figs. 53-59 represent response curves for each family of geophones. The response curves are similar for all geophones of a particular model except for constant voltage shift which can be calculated for each individual geophone.

Fig. 53. Geophone response curve, Type HS-10-1, Model K, 1.0 Hz, 41V/in./s (Geo Space Corp.).

Fig. 54. Geophone response curve, Type HS-10-1, Model K, 1.0 Hz, 15V/in./s (Geo Space Corp.).

Table 8. Specifications^a, Type HS-10-1 geophone, Model K 1.0 Hz, 41V/in./s

Frequency @ 5-10 mV	1.0 Hz
Frequency limits @ ± 0.1 Hz	0.9 to 1.1 Hz
DC resistance @ 25°C (DCR)	134,000 Ω
DCR Limits @ $\pm 5\%$	127,300 to 140,700 Ω
Number of turns	88,000 (total)
Wire size and type	No. 43 single solderize
Mean length of turn (MLT)	0.716 ft
Length of wire	63,008 ft
Intrinsic voltage sensitivity	41 V/in./s
Open circuit damping	34%
Open circuit damping limits @ $\pm 10\%$	30.6 to 37.4%
Open circuit overswing ration	10/3.20
Open circuit overswing ratio limits	10/3.65 to 10/2.80
Coil form weight, processed	393 g
Copper weight	387.4 g
Total moving mass	833 g
Total spring constant @ 1 Hz	3.28×10^4 dyn/cm
Air gap	0.3575 in. (0.9081 cm)
Flux, bottom of winding to top of winding	4.91×10^4 Mx
Gap area (per winding)	67.9 cm ²
Flux density (measured at bottom winding)	723 G
Total impedance @ 1 Hz	469,000 Ω
Motional impedance @ 1 Hz	335,000 Ω
(R + r) (b ₁ -b ₂)	260,000

^aSource: Geo Space Corp.

Table 9. Specifications^a, Type HS-10-1 geophone, Model K 1.0 Hz, 15V/in./s

Frequency @ 5-10 MV	1.0 Hz
Frequency limits @ ± 0.1 Hz	.9 to 1.1 Hz
DC resistance (DCR) @ 25°C	10,000 Ω
DCR limits @ $\pm 5\%$	9,500 to 10,500 Ω
Number of turns	25,000 (total)
Wire size and type	No. 37, single solderwire
Mean length of turn (MLT)	.0716 ft
Length of wire	17,900 ft
Intrinsic voltage sensitivity	15 V/in./s
Open circuit damping	.30%
Open circuit damping limits @ $\pm 10\%$	.27 to .33%
Open circuit overswing ratio	10/3.7
Open circuit overswing ratio limits @ $\pm 10\%$	10/4.1 to 10/3.3
Coil form weight, bare	.391 g*
Coil form weight, processed	.392 g*
Weight of wound coil	.897.5 g
Copper weight	.505.5 g (1.115 lb)
Weight allowance, rings and springs	.42.25 g
Total moving mass	.939.8 g
Top spring thickness	.0016 in.
Top spring preform	1.2 in.
Bottom spring thickness	.0016 in.
Bottom spring preform	1.2 in.
Total spring constant at 1.0 Hz	3.70×10^4 dyn/cm
Air gap	.03575 in. (0.9081 cm)
Flux, bottom of winding to top of winding	4.91×10^4 Mx
Gap area (per winding)	67.9 cm ²
Flux density (measured at bottom winding)	.723 G
Total impedance at 1.0 Hz	53,680 Ω
Motional impedance at 1.0 Hz	43,680
(R + r) (b ₁ - b ₀)	29,200

* Coil form weights indicated for bare processed forms include the weight ring with the wire (100.73 grams).

^aSource: Geo Space Corp.

Fig. 55. Geophone response curve, Type HS-10, Model K, 2.0 Hz, 3V/in./s (Geo Space Corp.).

Fig. 56. Geophone response curve, Type HS-1, Model K, 4.5 Hz, 0.55V/in./s (Geo Space Corp.).

Table 10. Specifications^a, Type HS-10 geophone, Model K 2.0 Hz, 3 V/in./s

Frequency	2.0 Hz
Frequency limits	1.85-2.15 Hz
DC resistance (DCR) @ 25°C	390 Ω
DCR limits @ ±5%	371-409 Ω
Number of turns	5000 (total)
Wire size and type	No. 30, single soldered
Mean length of turn (MLT)	0.716 in
Length of wire	3580 ft
Intrinsic voltage sensitivity	2.99 V/in./s
Open circuit damping	19%
Open circuit damping limits @ ± 10%	17.1-20.9%
Open circuit overswing ratio	10/5.43
Open circuit overswing ratio limits @ ± 10% damping	10/5.78-10/5.08
Coil form weight	197.08 g
Weight of wound coil	702.6 g
Copper weight	505.5 g
Weight allowance, rings and springs	26.25 g
Total moving mass	728.9 g
Total spring constant at 2.0 Hz	1.15×10^6 dyn/cm
Air gap	0.3575 in. (0.9081 cm)
Flux, bottom of winding to top of winding	4.91×10^4 Mx
Gap area (per winding)	67.9 cm ²
Flux density (measured at bottom winding)	723 G
Total impedance at 2.0 Hz	4281 Ω
Motional impedance at 2.0 Hz	3891 Ω
Product of DCR plus shunt load times loaded damping less open circuit damping	.697.3

^aSource: Geo Space Corp.

Table 11. Specifications^a, Type HS-1 geophone, Model K 4.5 Hz, 0.55 V/in./s

Frequency @ 20-30 MV	4.5 Hz
Frequency limits @ ± 0.75 Hz	3.75-5.25 Hz
DC resistance (DCR) @ 25°C	215 Ω
DCR limits @ $\pm 5\%$	205-225 Ω
Number of turns	1120 (total)
Wire size and type	No. 38, single solderize
Mean length of turn (MLT)	0.279 ft
Length of wire	312 ft
Intrinsic voltage sensitivity	0.559 V/in./s
Open circuit damping	22%
Open circuit damping limits @ $\pm 10\%$	19.8-24.2%
Open circuit overswing ratio	10/4.93
Open circuit overswing ratio limits @ $\pm 10\%$ damping	10/5.32-10/4.50
Coil form weight, bare (with weight ring)	21.583 g ^b
Coil form weight, processed (with weight ring)	21.714 g ^b
Weight of wound coil	28.941 g
Copper weight	7.227 g (0.0159 lb)
Weight allowance, rings and springs	0.616 g
Total moving mass	29.557 g
Top spring thickness (American Standard)	0.005 in.
Top spring preform (American Standard)	0.130 in.
Bottom spring thickness (American Standard)	0.0045 in.
Bottom spring preform (American Standard)	0.170 in.
Total spring constant at 4.5 Hz	2.37×10^4 dyn/cm
Air gap	0.0675 in. (0.1715 cm)
Flux, bottom of winding to top of winding	1.69×10^4 Mx
Gap area (per winding)	8.47 cm ²
Flux density (measured at bottom winding)	1995 G
Total impedance at 4.5 Hz	1553 Ω
Motional impedance at 4.5 Hz	1338 Ω
(R + r) (b _r - b ₀)	284.1

^aSource: Geo Space Corp.

^bWeight ring alone weighs 6.615 g

Fig. 57. Geophone response curve, Type L-4C, 1.0 Hz, 11V/in./s (Mark Products, Inc.).

Table 12. Specifications^a, Type L-4C geophone, 1.0 Hz

General geophone specifications	
Type	Moving dual coil, humbuck wound
Frequency	1.0 ± 0.05 Hz measured on 200-lb weight at 0.09 in./s
Frequency change with tilt	Less than 0.05 Hz at 5° from vertical
Frequency change with excitation	Less than 0.05 Hz from 0 to 0.09 in./s
Suspended mass	1000 g
Standard coil resistance	See table
Leakage to case	100 MΩ minimum at 500 V
Transduction power	8.8·10 ⁻³ watts inch second or 13.6 watts meter second
Open circuit damping	(b _c) = 0.28 critical
Current damping	$(b_c) = \frac{1.1R_c}{R_c + R_s}$
where: R _c = coil resistance-Ω	
R _s = shunt resistance-Ω	
Coil inductance	L _c = 0.0011 R _c
L _c in H	
Electric analog of capacity	$C_c = \frac{73,500}{R_c} (\mu F)$
Electric analog of inductance	L _m = 0.345 R _c (H)
Case Height	.5½ inches—13 cm
Case diameter	.3 inches—7.6 cm
Total density	3.7 grams cm ³
Total weight	.4½ pounds—2.15 kg
Operating temperature	Range: -20° to 140°F or -29° to 60°C
Operating pressure	.500 psi

Type L-4C geophone specifications (1.0 Hz, 11 V/in./s)

Coil resistance	12.9kΩ
Transduction	11 V/in./s
Coil inductance	14.19 H
Analog capacity equivalent	0.01 μF
Analog inductance equivalent	4450 H
Open circuit damping	0.28
Shunt for 0.50 critical damping	51.6 kΩ
Shunt for 0.70 critical damping	20 kΩ

^aSource: Mark Products, Inc.

Fig. 58. Geophone response curve, Type L-15B, 4.5 Hz, 1.5V/in./s (Mark Products, Inc.).

Fig. 59. Geophone response curve, Type L-15Δ, 4.5 Hz, 4V/in./s (Mark Products, Inc.).

Table 13. Specifications^a, Type L-15 geophone

General geophone specifications	
Distortion	Less than 0.2% @ 12 Hz with velocity of 0.7 in./s p-p
Standard frequency range	4.5 to 40 Hz
Frequency tolerance	±0.5 Hz or ±5%
Standard coil resistances (R_c)	24, 38, 60, 95, 150, 240, 380, 600, 960 Ω
Case to coil motion	0.080 in. p-p
Frequency change with tilt	Less than 0.1 Hz for vertical unit @ 20° (8 Hz)
Transduction, G	$G = 0.0483 \sqrt{R_c}$ V/in./s
Coil inductance, L_c	$L_c = 3.87 \cdot 10^{-4} R_c$ H
Basic unit	Diameter — 1.25 in.
Weight — 5.3 oz	Height — 1.28 in.
Type L-15B, geophone specifications (4.5-Hz)	
Coil resistance— Ω	960 9 400
Transduction—V/in./s	1.50 4.0
Coil inductance—H	0.370 3.7
Analog capacitance— μF	6.00 0.70
Analog inductance—H	203 1 910
Open circuit damping	0.32 0.39
Shunt for 0.50 critical	
damping— Ω	13 280 170 000
Shunt for 0.70 critical	
damping— Ω	5785 56 000

^aSource: Mark Products, Inc.

Fig. 60. Accelerometer response curves, Model 305A, $\pm 10g$ input at 72°F: (a) $\pm 15V$ dc power, based on a typical production lot; (b) typical unit with supply voltages indicated (Sundstrand Data Control, Inc.).

Table 14. Specifications^a, Model 305-A accelerometer

	As current source	As voltage source
Range	±50 g	±50 g
Sensitivity (±1%)	0.200 ma/g	100 mV/g
Noise: 1 MHz to 8 MHz (less than)	10 µa, rms	5 mV, rms
below 1 MHz (less than)	2 µa, rms	1 mV, rms
DC to 1 Hz (resolution)	5 micro g (0.001 µa)	5 micro g
Output impedance	1.0 megohm, min.	500 Ω
Frequency response (within ±5%; with ±15 V DC pwr)	DC to 500 Hz	DC to 500 Hz
Natural frequency, undamped (nominal)	1000 Hz	100 Hz
Damping (approximate)	0.65	0.6
Supply voltage (±10%)	±15 V DC	±15 V DC
Supply current at 0 g	5 ma (nominal)	5 ma (nominal)
Supply current at 50 g	20 ma (max.)	20 ma (max.)
Electrical isolation at 50V DC (pins to case)	50 MΩ	50 MΩ
Linearity (independent)	0.01% F.S. (any range)	0.1% F.S. (any range)
Hysteresis & repeatability	0.0005 g	0.0005 g
Output at 0 g (maximum)	10 µa	5 mV
Zero shift with supply voltage	1 µa/V (max.)	0.5 mV/V (max.)
Sensitivity shift with supply voltage	0.05%/V (max.)	0.05%/V (max.)
Temperature range (storage & operating)	-65 to +185°F	-65 to +185°F
Temperature zero shift (max.)	0.03 g/100°F	0.03 g/100°F
Temperature sensitivity (max.)	0.02%/°F	0.01%/°F
Transverse acceleration: DC to 5 Hz	±50 g	±50 g
5 Hz to 2 K Hz	20 g (peak)	20 g (peak)
DC output from vibration (rectification error)	0.001 g/g (nominal)	0.001 g/g (nominal)
at 250 Hz & 10 g peak		at 250 Hz & 10 g peak
Cross coupling coefficient (pendulosity error)	none	none
Case alignment (to true sensitivity axis)	±1/2° (maximum)	±1/2° (maximum)
Acceleration limit (non-operating)	100 g	100 g
Shock limit (5 msec pulse)	100 g max. for any axis	100 g max. for any axis
Weight	3.4 oz	3.4 oz
Mounting	stud mounting or use of appropriate adaptor	
Suspension of seismic element	nonpendulous, true-translational flexure suspension	

^aSource: Sundstrand Data Control, Inc.

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