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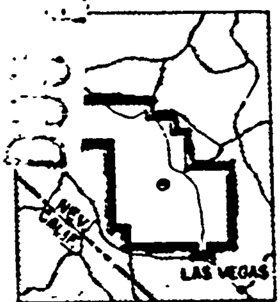
OPERATION

PLUMBBOB



NEVADA TEST SITE

MAY-OCTOBER 1957

Project 1.9

SPECTRA of GROUND SHOCKS PRODUCED by NUCLEAR DETONATIONS (U)

Issuance Date: August 17, 1959

HEADQUARTERS FIELD COMMAND
DEFENSE ATOMIC SUPPORT AGENCY
SANDIA BASE, ALBUQUERQUE, NEW MEXICO

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OPERATION PLUMBBOB—PROJECT 1.9

SPECTRA of GROUND SHOCKS PRODUCED by NUCLEAR DE[redacted]ATIONS

J. F. Halsey, [redacted]
and M. V. Barton,

Air Force Ballistic Missile Div[redacted]
Air Research and Development Command,
Inglewood, Calif[redacted]

ABSTRACT

The problem of defining design parameters for structures capable of withstanding blast-induced ground shock suggested the use of shock spectra as a suitable means of presenting environmental conditions. Self-contained mechanical reed gages, capable of measuring the displacement shock spectrum over a frequency range of 3 to 300 cps in any one direction, were placed on Shots Stokes, Smoky, Galileo, Whitney, and Charleston. Canisters containing the gages were normally placed with tops flush to the ground level at predicted pressure levels of approximately 100 psi; however, on Shot Smoky two additional gages were placed on the floor of an earth-covered-personnel shelter, and two gages were installed on a concrete block for Shot Whitney.

A composite plot of the results of surface gages from Shots Smoky, Galileo, and Whitney ~~(overpressures from 116 to 146 psi)~~ indicates some ~~very~~ definite trends. The displacements are ~~two~~ to ~~three~~ times higher at ~~three~~ cps for the vertical component ~~(3 inches to 5½ inches)~~ than for the radial component ~~(1 inch to 2 inches)~~. The rate of decrease of displacement with increasing frequency is greater for the vertical component than for the radial component. A comparison of the results from the surface gages and those within the structure on Shot Smoky indicates an attenuation factor of three for vertical displacements, with no appreciable change in the radial direction.

[redacted]

FOREWORD

This report presents the final results of one of the 46 projects comprising the military-effect program of Operation Plumbbob, which included 24 test detonations at the Nevada Test Site in 1957.

For overall Plumbbob military-effects information, the reader is referred to the "Summary Report of the Director, DOD Test Group (Programs 1–9)," ITR-1445, which includes: (1) a description of each detonation, including yield, zero-point location and environment, type of device, ambient atmospheric conditions, etc.; (2) a discussion of project results; (3) a summary of the objectives and results of each project; and (4) a listing of project reports for the military-effects program.

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CONTENTS

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SPECTRA of GROUND SHOCKS PROUCED by NUCLEAR DETONATIONS

OBJECTIVE

The objective of Project 1.9 was to obtain the displacement velocity and acceleration-shock spectra of ground shocks produced by nuclear devices for use in the design of missile bases and operational equipment when subjected to a similar environment. The shock spectrum is a plot showing the peak response of a linear, variable frequency oscillator (of a single degree freedom) to a specific blast wave, as a function of the frequency of the oscillator.

BACKGROUND

In the past, a limited number of measurements had been made of the ground motions caused by blasts in the form of ground acceleration, velocity, or displacement versus time records. Such information was useful in predicting the response of ground-based structures. Some of these records were analyzed by analogue or digital computers for presentation in terms of shock spectra, which resulted in a plot of the peak response of a linear, variable frequency oscillator (of single degree of freedom) as a function of the frequency of the oscillator. The information in this form was used to estimate the peak responses of single degree-of-freedom structures. More recently (Reference 1) it has been shown that estimates of the upper bounds of response of complex structures (many degrees of freedom) can also be made by means of shock spectra.

Shock spectra are of considerable interest and usefulness. Although theoretically they can be obtained by the analysis of acceleration time records, there are many practical difficulties associated with the determination of the low-frequency components both in the analyses of the ground records and the acceleration measurement. There are also difficulties in interpretation of the statistical scatter and variations of instrument damping of the acceleration measurements. Since for many design purposes, it is desirable to specify the ground motions in terms of shock spectra, a direct measurement by means of shock gages for a variety of blasts, locations and soil conditions is indicated. Shock gages have been used successfully in many fields, such as aircraft-landing impact, torpedo entry, and shipboard vibration.

THEORY

Complete discussions of the theory and application of shock spectra are given in References 1 and 2. Briefly, however, if a shock is applied to a single degree-of-freedom system, such as an idealized mass on the end of a cantilever spring, the motion of the mass, relative to the accelerated support, is governed by:

$$\ddot{q} + 2\epsilon\omega\dot{q} + \omega^2 q = -a(t) \qquad (1.1)$$

[redacted]

where: q = displacement of mass (inches) relative to accelerated support
$\dot{q}$ = velocity of mass (in/sec)
$\ddot{q}$ = acceleration of mass (in/sec^2)
ϵ = ratio of damping to critical viscous damping
ω = frequency of spring mass system (rad/sec)
$a(t)$ = shock acceleration (in/sec^2) (function of time)

The peak response in terms of displacement, velocity or acceleration of the mass to each side of the position of static equilibrium can be obtained from the solution of Equation 1.1 if the dynamic characteristics of the system are known and the acceleration input is specified. The peak responses to given shock acceleration can also be measured directly by means of a shock gage.

Formally, the peak response for systems with $\epsilon \ll 1$ is given by:

$$q_{max}(\omega,\epsilon) = \max_{t>0} \left| \frac{1}{\omega} \int_0^t a(\tau) e^{-\epsilon\omega(t-\tau)} \sin \omega(t-\tau) d\tau \right| \tag{1.2}$$

which can be represented as a displacement shock spectrum D,

$$D = q_{max}(\omega,\epsilon) \tag{1.3}$$

when plotted as frequency of the oscillator versus peak displacement of the mass relative to the base which is being accelerated.

The velocity shock spectrum is defined as:

$$V = \omega D \tag{1.4}$$

which is not the true peak velocity of the mass, but is of interest in the determination of the maximum strain energy in a structure.

The acceleration shock spectrum is defined as:

$$A = \omega^2 D \tag{1.5}$$

and can be shown to be the absolute acceleration of the mass (for small damping), namely:

$$A = \max \left| \ddot{q} + a(t) \right| \tag{1.6}$$

In general, a shock gage of the type used in these tests directly measures the displacement shock spectrum given by Equation 1.3 for 10 values of frequency. Plots of the displacement-shock spectra are given as displacement D (inches) versus frequency f (cps). The velocity-shock spectra are obtained by multiplying the values of the displacement-shock spectra by their respective frequencies in radians per second to give V (inches per second) versus f (cps). The acceleration spectra are obtained by multiplying the value of the velocity spectra by frequency so that it can be represented by a plot of acceleration (A) in inches per second squared, which can be expressed as acceleration in g versus frequency.

OPERATIONS

Project 1.9 participated in Shots Stokes, Smoky, Galileo, Whitney, and Charleston.

Activities at the test site were limited to placement of instruments, recovery of records, and recovery of instruments.

INSTRUMENTATION

Twelve shock gages and protecting canisters were used on the tests.

The shock gage was a completely self-contained mechanical unit requiring no electronics or communication channels. It consisted essentially of 10 masses attached to cantilever springs which were mounted on two sides of a vertical plate as shown in Figure 1. The natural frequencies of the spring-mass systems are approximately 3, 10, 20, 40, 80, 120, 160, 200, 250, and 300 cps.

Peak responses to the shock input for each spring-mass system are obtained on polished, smoked, record plates which are marked by the movement of a stylus attached to each mass. The length of the marks (measurement of displacement) is determined by use of a microscopic micrometer in the laboratory.

Protection for the gage was obtained by placement inside a cylindrical canister two feet in diameter and approximately two feet deep. Figure 2 shows the canister used. Transmission of shock input to the gage (either in the vertical or horizontal direction) was secured by bolting the gage in the desired position to the one-inch-base plate of the canister.

Installation. The sequence of installation of gages, when used for measurements in the free-field were: (1) excavation of a 27-to-36-inch-cubical hole at the desired pressure range; (2) placement of protective canister (400 pounds total weight) as shown in Figure 2; (3) backfill around canister using select sand (concrete)[1]; (4) placement of gage (130 pounds) in canister; (5) placement of polished record plates (two per gage); (6) careful placement and bolting of canister lid (rough handling could excite the gages); and (7) placement of three layers of sandbags over the lid for thermal and nuclear radiation protection.

Two canisters were affixed to the floor of a German shelter (Structure 8-3.7-8011) in the Shot Smoky area by means of anchor bolts. Two canisters were fastened to a concrete anchor block in the Shot Whitney area in a similar manner, except that availability dictated the use of $^3/_4$-inch bolts in lieu of 1-inch bolts. As a further precaution a bridle tie-down (consisting of $^1/_4$-by-5-inch steel plate and band) fastened by means of four bolts to the concrete was used. The canisters were surrounded by a minimum of three thicknesses of sandbags.

Recovery. Recovery of the records for free-field measurements was accomplished by: (1) moving or sweeping sandbag debris from cover; (2) unbolting and removing the lid; and (3) removing wing-nut from gage and slipping out polished record plates in a careful manner.

Records were recovered from all gages installed, except those two in the Shot Whitney area which were affixed to the anchor block. Those canisters and gages were found at a point some 30 feet from their original position, and examination revealed that the anchor bolts in the concrete had either pulled out or had sheared off. Those canisters and gages were considered a total loss. Two free-field measurements were obtained in this area.

Calibration. While the computed design natural frequency of each spring mass was

[1]Compaction was obtained through use of hand tamping and water. It is estimated that a compaction of 90 percent of maximum density at optimum moisture content was obtained.

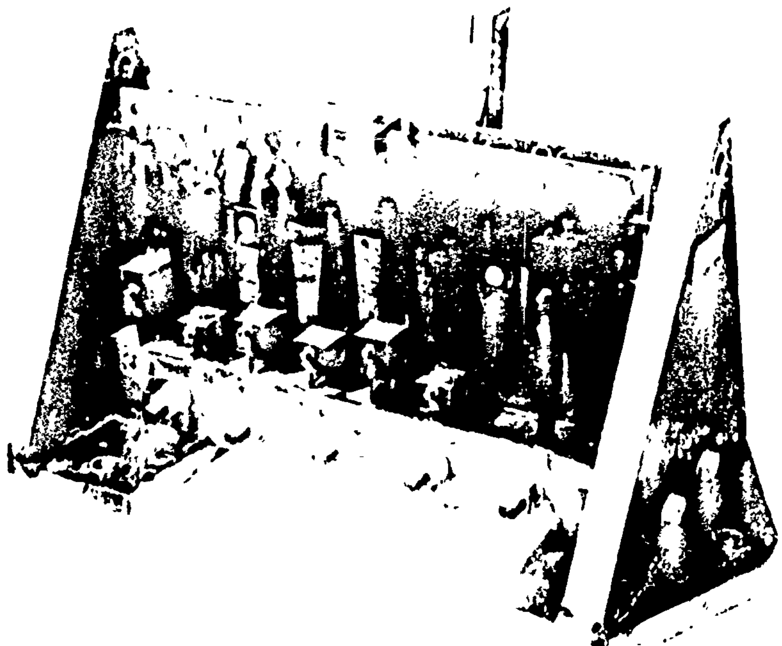

Figure 1 Shock spectra gage.

Figure 2. Typical placement of protective canister.

known, calibration of each reed on each gage was required so that any variation in fabrication and assembly would be accounted for.

The natural frequency was determined by use of a shake table for excitation, with frequency sweep and resonant points being obtained through use of a Strobotac instrument. The degree of damping of each spring-mass system was established by obtaining a trace of the light reflected (from a source) by a mirror attached to the mass, and noting the decay of the trace during free oscillation. Damping was found to be 0.5 percent.

Data Requirements. The specification of design parameters as discussed above and in References 1 and 2 required that the shock spectra be obtained for the preselected overpressure level of 100 psi. Statistical considerations, variable ground conditions and placement suggested the use of gages on more than one event.

With these ground rules in mind it was decided to use Shot Stokes as a preliminary test of the instrumentation. Two radial and two vertical gages were placed at a point 170 feet east of ground zero where they experienced an overpressure of 33 psi.

Shot Smoky afforded the opportunity of placement of gages both within a structure, and in the free-field at approximately the 100-psi level. One radial and one vertical gage were placed within Structure 8-3.7-8011 at 1,005 feet from ground zero. Adjacent to the structure and separated by a distance between gages of five feet, one radial and two vertical gages were placed. The recorded overpressure level was 116 psi.

At a point 650 feet north of Shot Galileo ground zero and separated by five feet, one radial and two vertical gages were placed with a resulting overpressure level of 130 psi.

The desire to obtain the shock spectra of the acceleration induced in a large mass of concrete led to the installation of one radial and one vertical gage 600 feet west of Shot Whitney ground zero where one of the Operation Teapot tower guy cable anchor blocks was located. On the same radius, five feet from the block and separated by the same distance, one radial and one vertical gage were placed. Extremely hard excavation led to use of power equipment, so that the canister top was approximately 18 inches below ground level instead of being flush as in the other cases. The overpressure level was 146 psi.

Locations for Shot Charleston were dictated by the desire to obtain measurements over a range of overpressure levels which could possibly lead to a correlation of the shock spectra with overpressure level. Therefore, using calculations from an expected high yield of the device, gages were placed 1,100, 1,300, 1,500, and 2,300 feet south of ground zero. Anticipated overpressure levels were 100, 75, 50, and 25 psi at the respective locations, but a low yield of the device gave levels of only 20, 18, 15, and 12 psi.

Ballistic Research Laboratories (BRL) furnished overpressure determinations for all shots.

RESULTS

The experimentally determined peak-displacement of the masses in the vertical and radial directions of single degree-of-freedom-systems for ten frequencies and 0.5 percent damping are presented as Table 1 and graphs Figures 3 through 24.

With the exception of the two measurements taken inside a shelter (Shot Smoky gages 5 and 6, Figures 17 and 6), all measurements were at or near (within three feet) ground surface.

Displacement-shock spectra in the vertical direction ranged from slightly less than six inches to less than 0.001 inch. Comparable values for the radial directions were two inches to 0.0007 inch. The accuracy of measurements was probably better at the low fre-

TABLE 1 DISPLACEMENT SHOCK SPECTRUM

f, natural frequency; D, peak displacement

Radial Direction				Vertical Direction			
f	D	f	D	f	D	f	D
cps	in	cps	in	cps	in	cps	in
Shot Stokes, Surface, 33-psi Overpressure							
Gage 1		Gage 3		Gage 2		Gage 4	
2.56	—	2.66	0.199	2.56	0.710	2.74	0.516
8.92	0.137	8.87	0.0260	8.92	0.569	9.66	0.440
22.0	0.0318	22.2	0.0248	22.0	0.101	20.4	0.165
36.0	0.0451	36.5	0.0093	36.0	0.0498	32.8	0.0633
90.0	0.0231	92.0	0.0074	90.0	0.0385	88.0	0.0560
134	0.0056	132	0.0018	131	0.0128	133	0.0309
184	0.0121	176	0.0017	179	0.0088	185	0.0154
228	0.0027	224	0.0020	209	0.0030	22[illegible]	0.0066
269	0.0065	279	—	268	0.0027	263	0.0026
339	—	312	—	303	0.0033	293	0.0012
Shot Smoky, Inside Shelter, 116-psi Overpressure							
Gage 5		—		Gage 6		—	
2.72	2.25			2.54	1.62		
9.37	0.453			8.72	0.906		
22.3	0.113			21.9	0.336		
36.9	0.0451			37.0	0.0744		
95.0	0.0185			92.0	0.0167		
138	0.0101			138	0.0099		
184	0.0099			185	0.0034		
234	0.0041			246	0.0051		
285	0.0022			280	0.0039		
296	0.0031			363	0.0038		
Shot Smoky, Surface, 116-psi Overpressure							
Gage 9		—		Gage 7		Gage 8	
2.55	1.95			2.60	5.45	2.53	4.53
9.12	0.359			8.56	1.52	8.82	1.46
22.4	0.189			22.4	0.845	22.6	0.525
33.9	0.131			37.4	0.254	37.1	0.205
93.0	0.0227			91.0	0.132	93.0	0.103
107	0.0149			132	0.0673	137	0.0450
181	0.0107			187	0.0221	180	0.0199
203	0.0042			238	0.0106	236	0.0122
293	0.0055			280	0.0112	294	0.0055
357	0.0027			335	0.0066	328	0.0066
Shot Galileo, Surface, 130-psi Overpressure							
Gage 11		—		Gage 10		Gage 12	
2.35	0.653			2.48	4.10	2.47	4.25
8.63	0.377			8.26	0.946	8.23	1.22
22.5	0.164			22.7	0.320	21.0	0.475
36.5	0.0453			37.1	0.314	35.0	0.280
95.0	0.0349			94.0	0.140	94.0	0.121
138	0.0184			138	0.0441	136	0.0267
186	0.0103			187	0.0146	178	0.0442
237	0.0032			234	0.0098	229	0.0161
294	0.0046			272	0.0139	300	0.0121
317	0.0029			365	0.0046	339	0.0053

TABLE 1 CONTINUED

f, natural frequency, D, peak displacement

Radial Direction				Vertical Direction			
f	D	f	D	f	D	f	D
cps	in	cps	in	cps	in	cps	in
Shot Whitney, Surface, 146-psi Overpressure							
Gage 4 *		—		Gage 3 *		—	
2.71	1.60			2.66	3.10		
9.66	0.260			8.97	1.47		
20.4	0.119			22.2	0.788		
32.8	0.0831			36.5	0.348		
86.0	0.0187			92.0	0.141		
131	0.0118			132	0.0992		
185	0.0088			176	0.0402		
220	0.0064			227	0.0090		
269	0.0026			284	0.0152		
314	0.0054			330	0.0080		
Shot Charleston, Surface †							
Gage 5 (20-psi overpressure)		Gage 9 (18-psi overpressure)		Gage 6 (20-psi overpressure)		Gage 8 (18-psi overpressure)	
2.72	0.263	2.55	0.265	2.54	—	2.53	0.728
9.37	0.111	9.12	0.0838	8.72	0.280	8.82	0.253
22.3	0.0900	22.4	0.0691	21.9	0.221	22.6	0.194
36.9	0.0404	33.9	—	37.0	—	37.1	0.0826
95.0	0.0190	93.0	0.0096	92.0	0.0246	93.0	0.0208
138	0.0100	107	0.0050	138	0.0093	137	0.0048
184	0.0014	181	0.0023	185	0.0062	180	0.0025
234	0.0030	203	0.0026	246	0.0023	236	0.0015
285	0.0026	293	0.0019	280	0.0023	294	0.0015
296	0.0020	357	0.0009	363	0.0007	328	0.0016
Gage 11 (15-psi overpressure)		—		Gage 10 (15-psi overpressure)		Gage 12 (12-psi overpressure)	
2.35	0.879			2.48	0.407	2.47	0.492
8.63	0.262			8.26	0.163	8.23	0.177
22.5	0.195			22.7	0.0726	21.0	0.207
36.5	0.0804			37.1	0.0231	35.0	0.0786
95.0	0.0246			94.0	—	94.0	0.0193
138	0.0033			138	—	136	0.0101
186	0.0020			187	—	178	0.0053
237	0.0019			234	—	229	0.0005
294	0.0011			272	—	300	—
317	0.0007			365	0.0009	339	0.0006

* Canister tops were about 18 inches below ground level in hard ground. Two other gages bolted to concrete pads in the same vicinity were knocked loose and data was lost.

† Tangential direction for Gage 7 (20-psi overpressure): insignificant displacement.

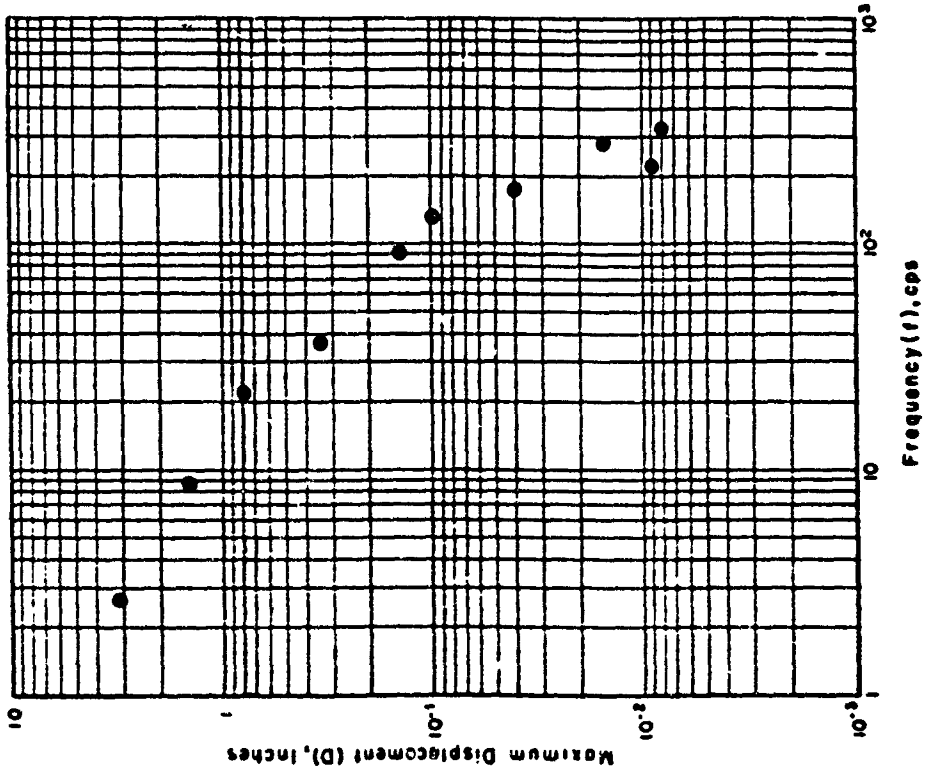

Figure 3 Displacement shock spectrum, vertical direction; Shot Whitney, Gage 3, 146-psi overpressure, surface.

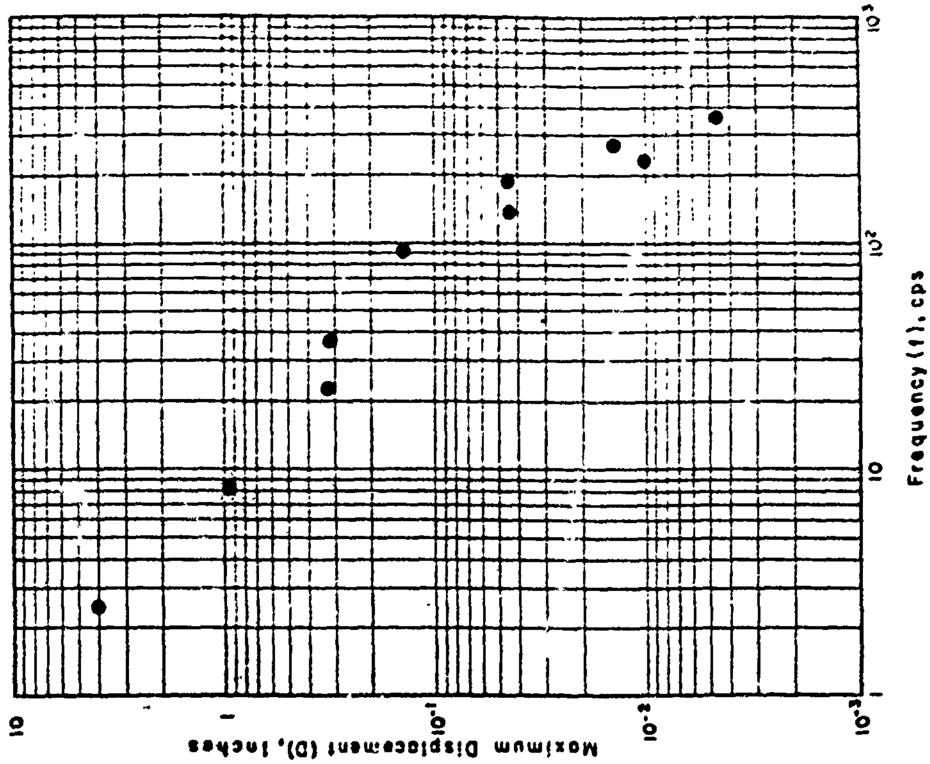

Figure 4 Displacement shock spectrum, vertical direction; Shot Galileo, Gage 10, 130-psi overpressure, surface.

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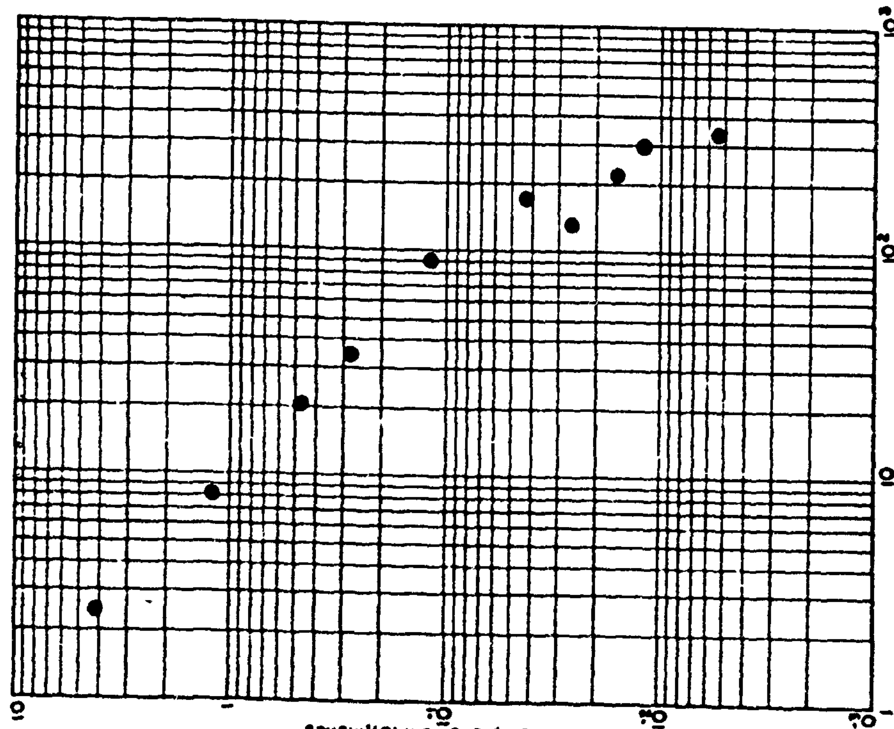

Figure 5 Displacement shock spectrum, vertical direction; Shot Galileo, Gage 12, 140-psi overpressure, surface.

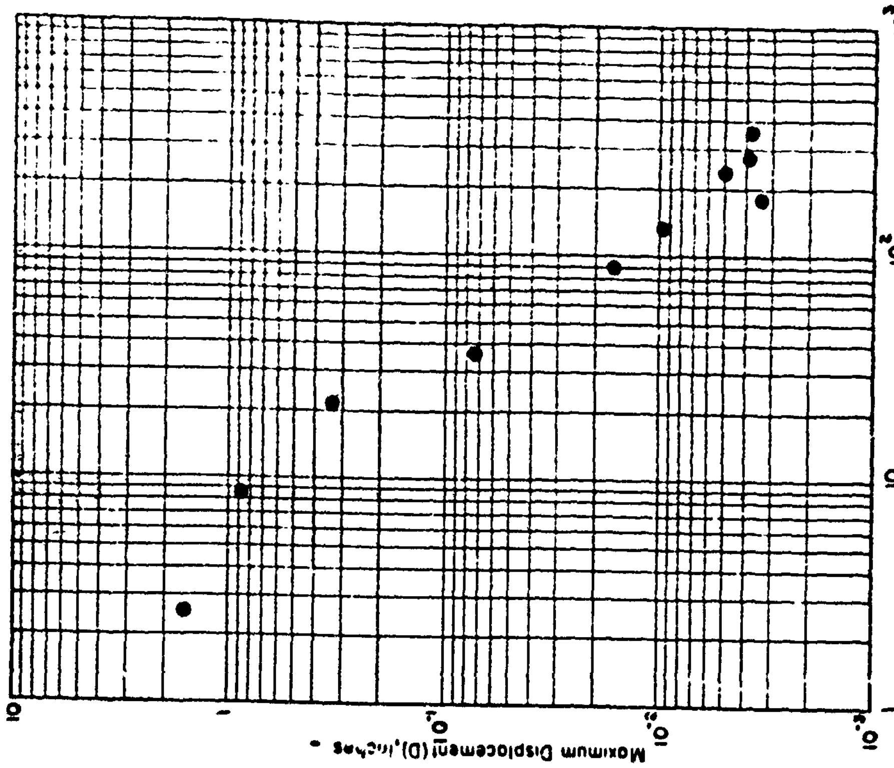

Figure 6 Displacement shock spectrum, vertical direction, Shot Smoky, Gage 6, 116-psi overpressure, inside shelter.

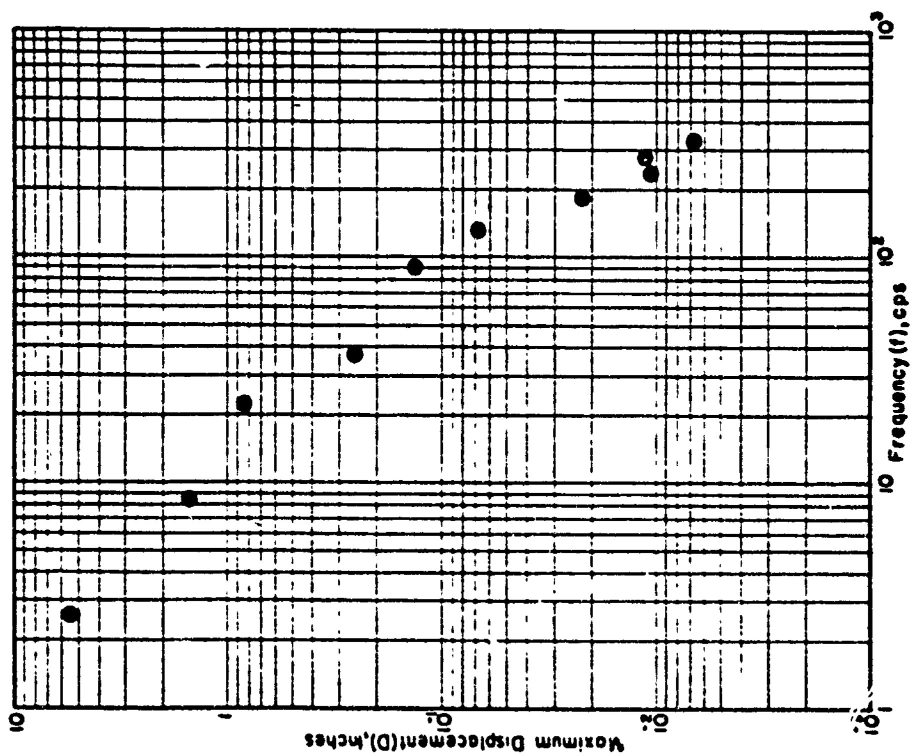

Figure 7 Displacement shock spectrum, vertical direction; Shot Smoky, Gage 7, 116-psi overpressure, surface.

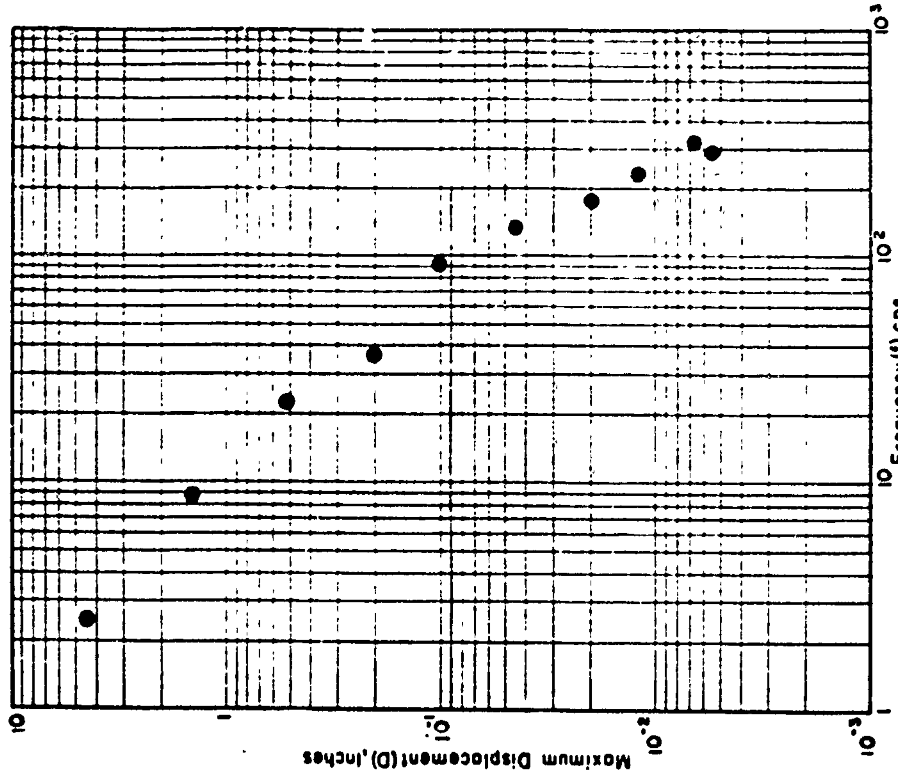

Figure 8 Displacement shock spectrum, vertical direction, Shot Smoky, Gage 8, 116-psi overpressure, surface.

quencies, (less than 10 cps) because of the difficulty of reading the small record marks at the higher frequencies. The records obtained from Shot Stokes are considered most unreliable, because this shot was used as a preliminary test for the instruments using a different type of record plate, which required the scratching on a dyed surface, later re-

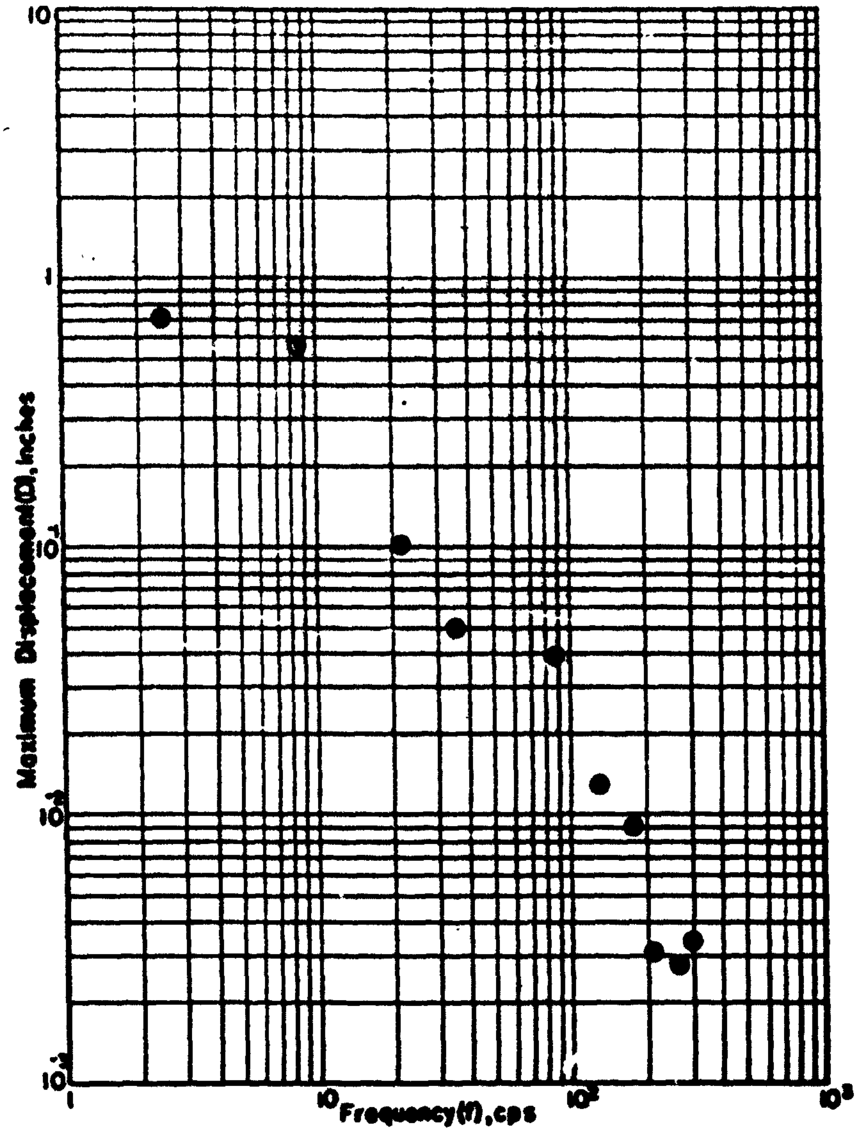

Figure 9 Displacement shock spectrum, vertical direction; Shot Stokes, Gage 2, 33-psi overpressure, surface

placed by a smoked surface. The results from Shot Charleston should also be considered with caution because the unexpected low yield produced lower impulses than the gages were designed to record accurately.

Perhaps of most interest were the combined plots of results for similar overpressure regions (116 to 146 psi) of the displacement, velocity and acceleration shock spectra in

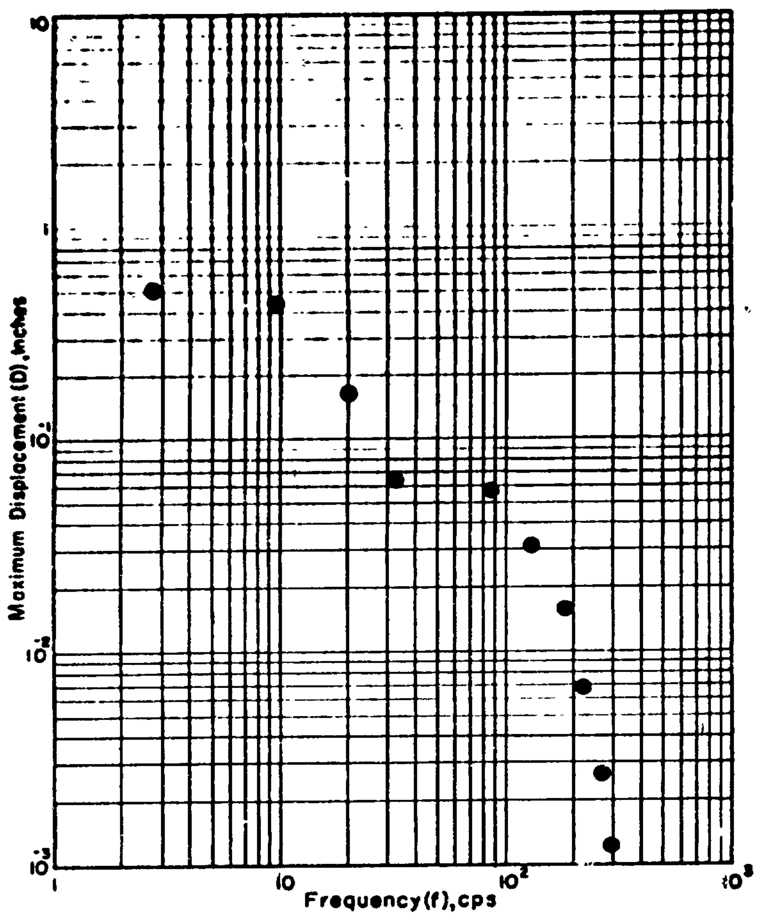

Figure 10 Displacement shock spectrum, vertical direction, Shot Stokes, Gage 4, 33-psi overpressure, surface.

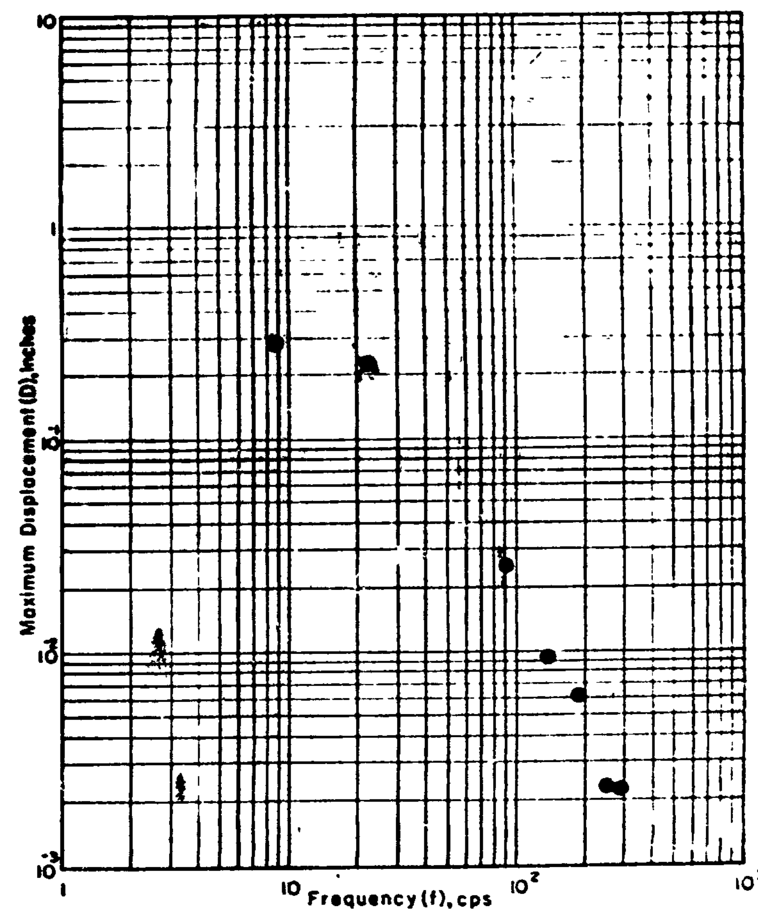

Figure 11 Displacement shock spectrum, vertical direction, Shot Charleston, Gage 6, 20-psi overpressure, surface

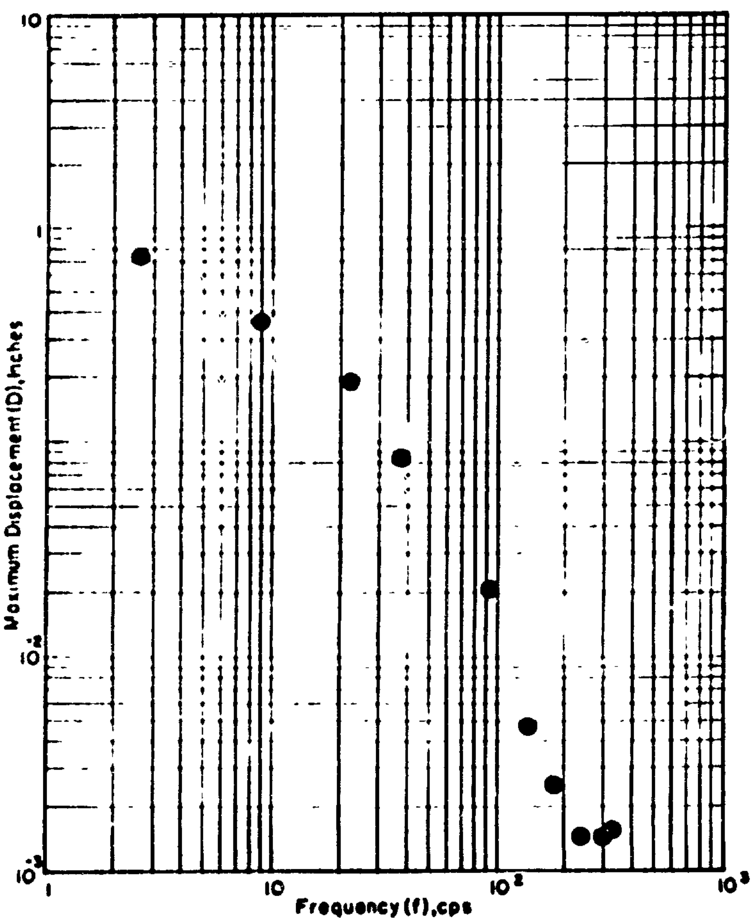

Figure 12 Displacement shock spectrum, vertical direction; Shot Charleston, Gage 8, 18-psi overpressure, surface

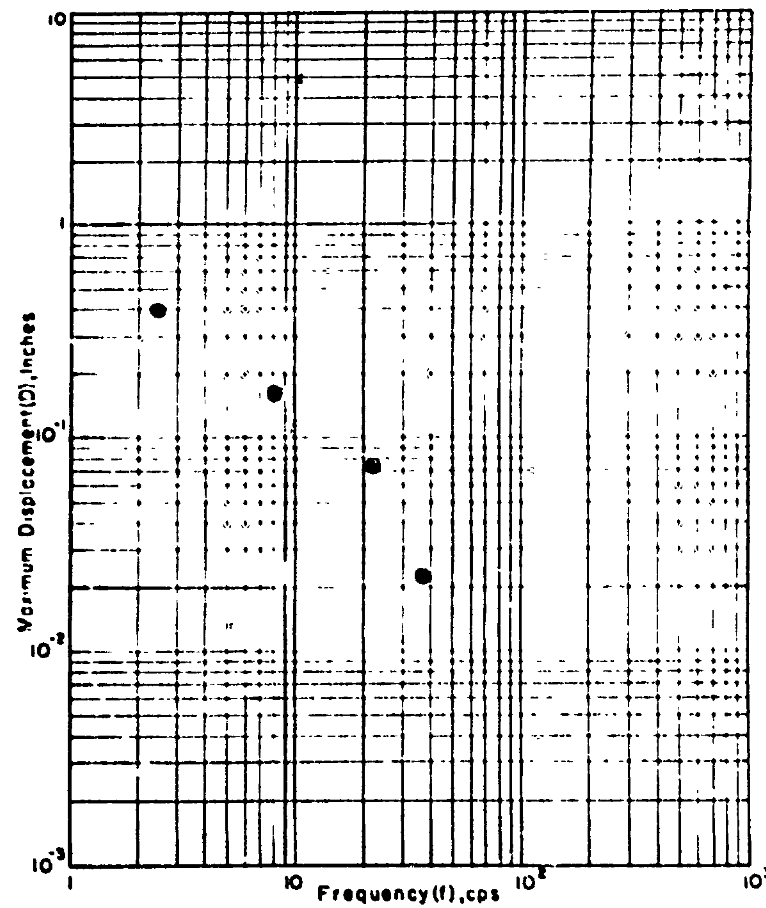

Figure 13 Displacement shock spectrum, vertical direction, Shot Charleston, Gage 10, 15-psi overpressure, surface

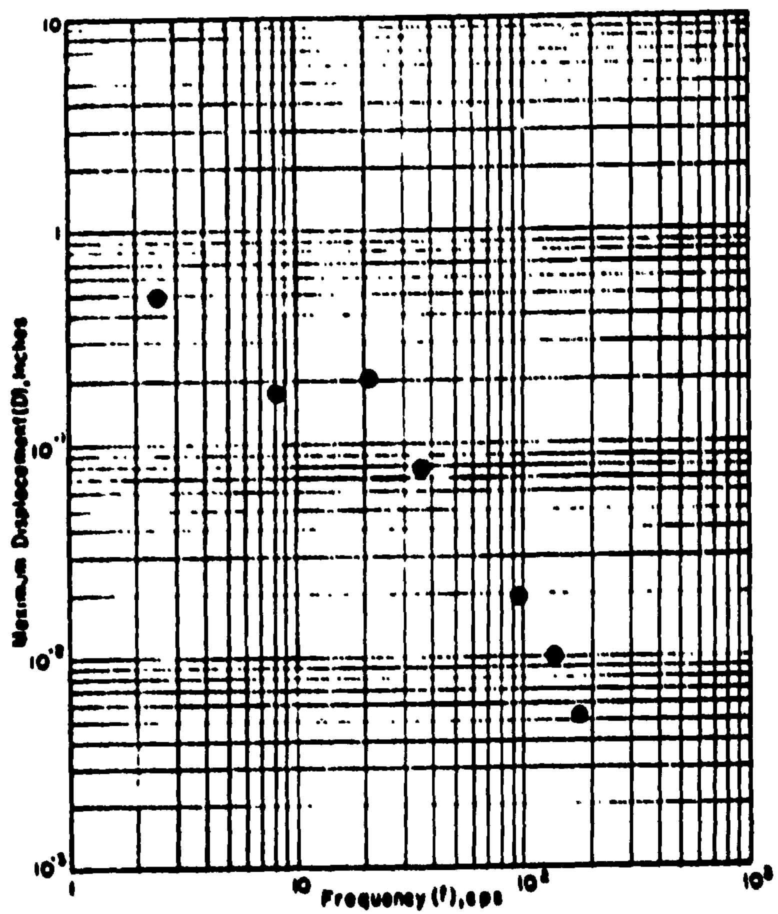

Figure 14 Displacement shock spectrum, vertical direction; Shot Charleston, Gage 12, 12-psi overpressure, surface.

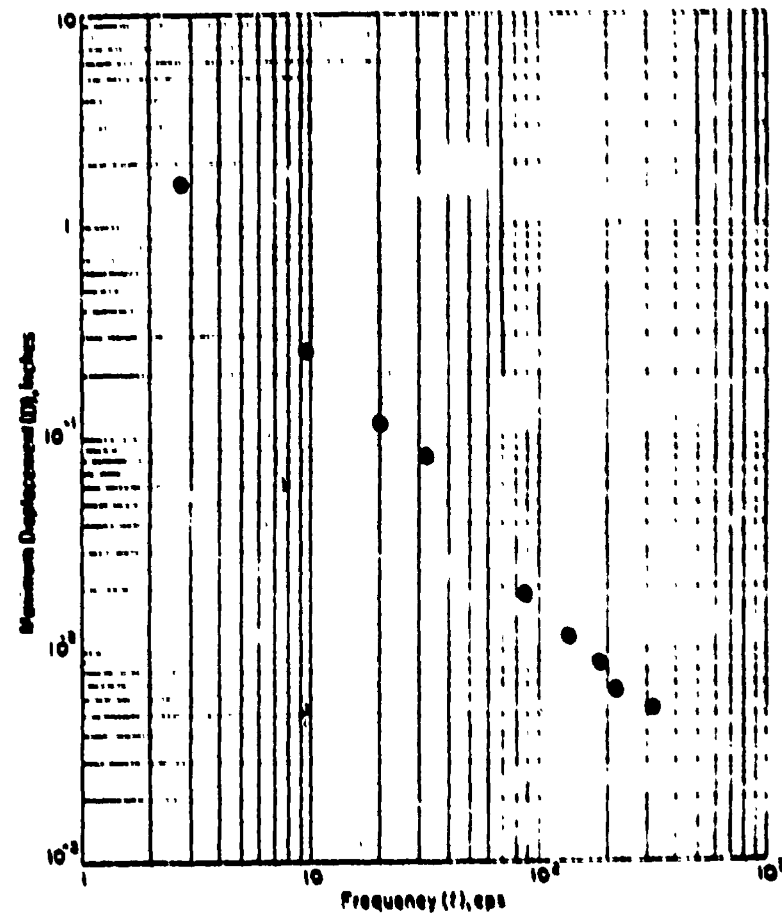

Figure 15 Displacement shock spectrum, radial direction, Shot Whitney, Gage 4, 140-psi overpressure, surface

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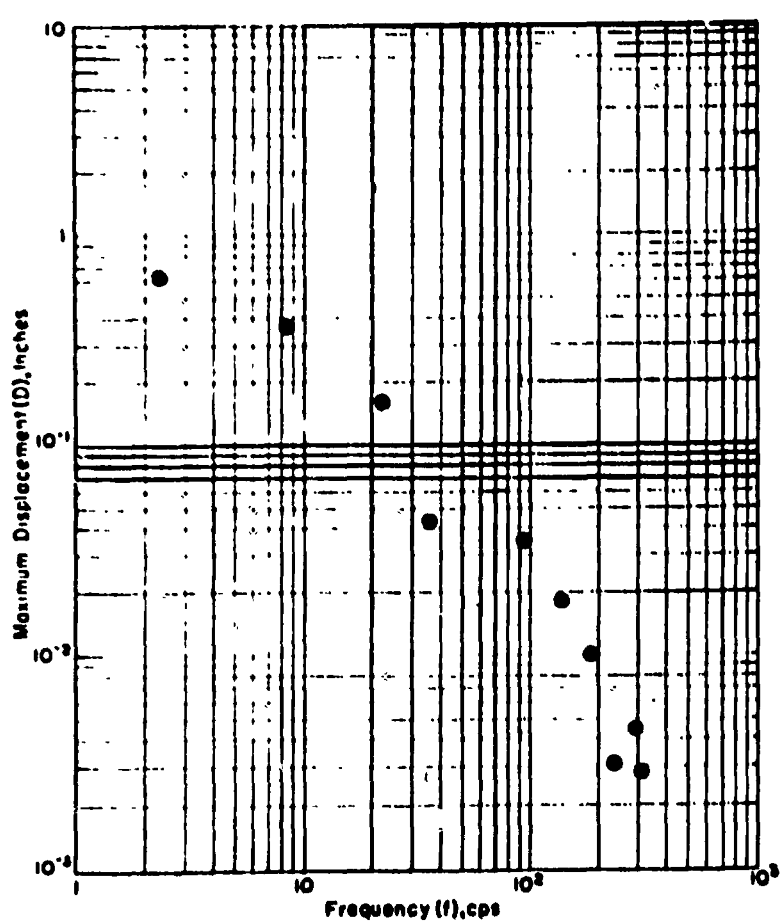

Figure 16 Displacement shock spectrum, radial direction; Shot Galileo, Gage 11, 130-psi overpressure, surface

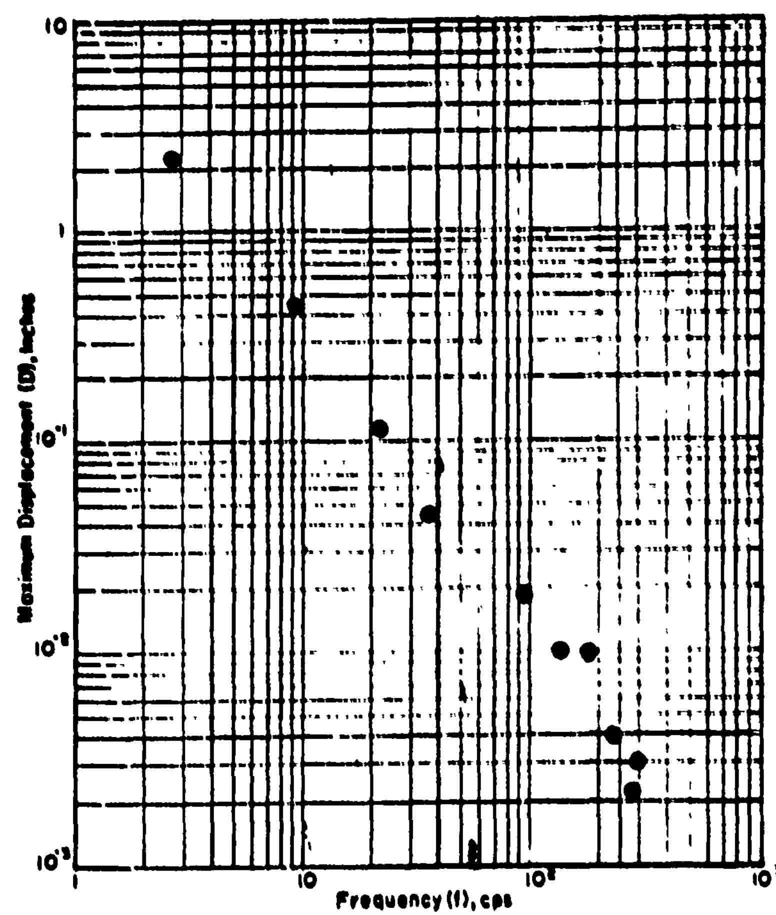

Figure 17 Displacement shock spectrum, radial direction, Shot Smoky, Gage 5, 110-psi overpressure, inside shelter

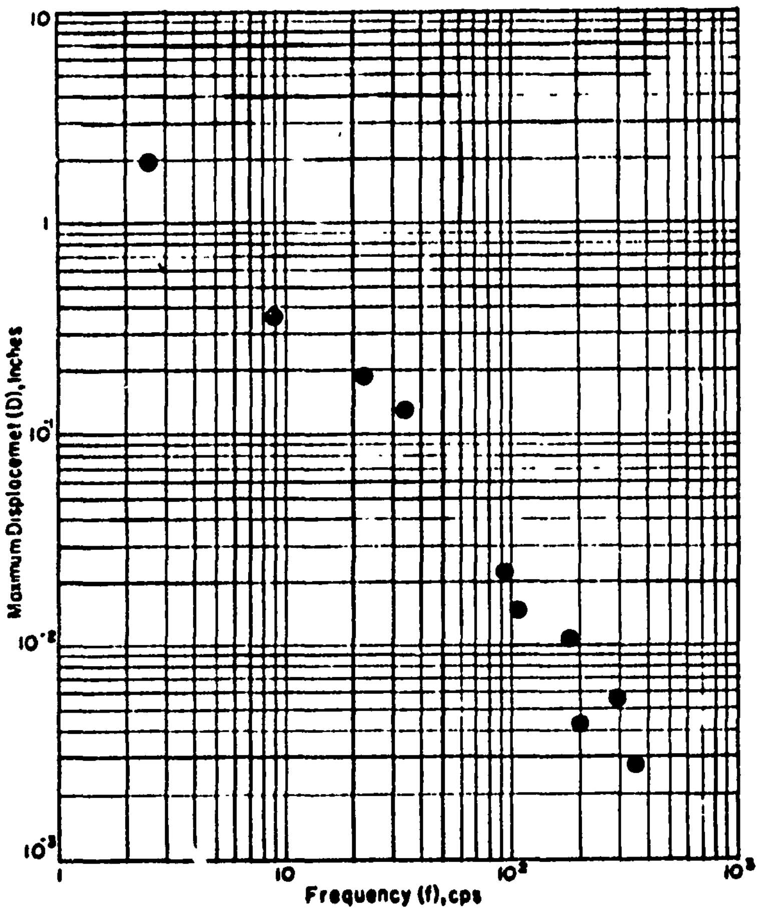

Figure 18 Displacement shock spectrum, radial direction; Shot Smoky, Gage 9, 116-psi overpressure, surface.

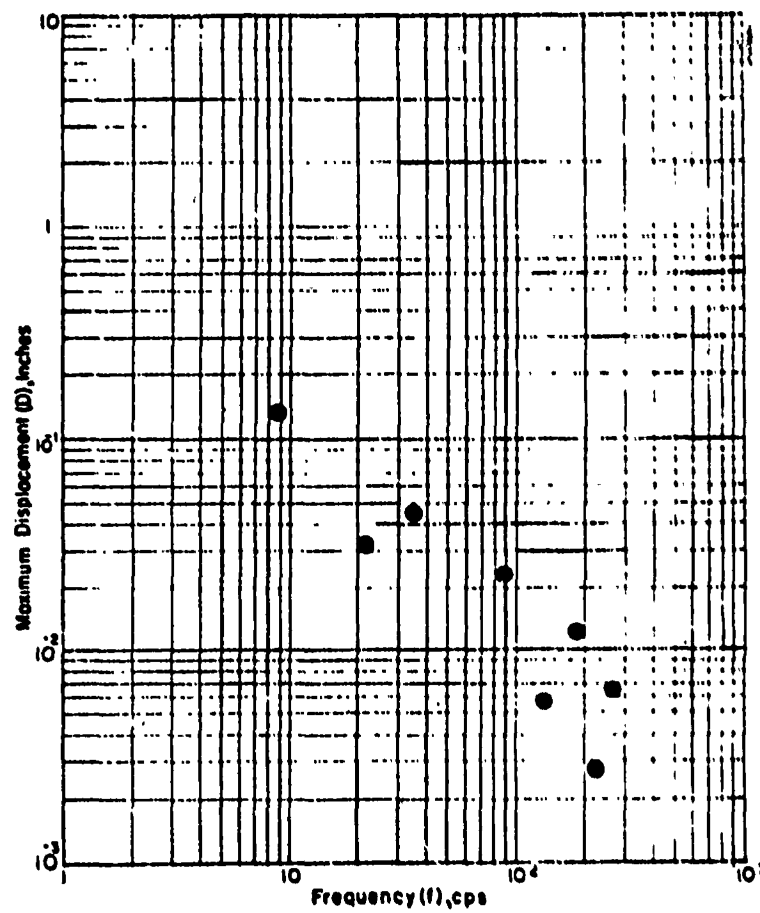

Figure 19 Displacement shock spectrum, radial direction; Shot Stokes, Gage 1, 33-psi overpressure, surface.

the vertical and radial directions, (Figures 25 through 27 and 29 through 31). Although there was some scatter in the data for the displacement shock spectra, as might be expected from the statistical nature of the phenomena, definite trends were indicated. The rate of decrease with frequency was greater for the vertical component than the radial

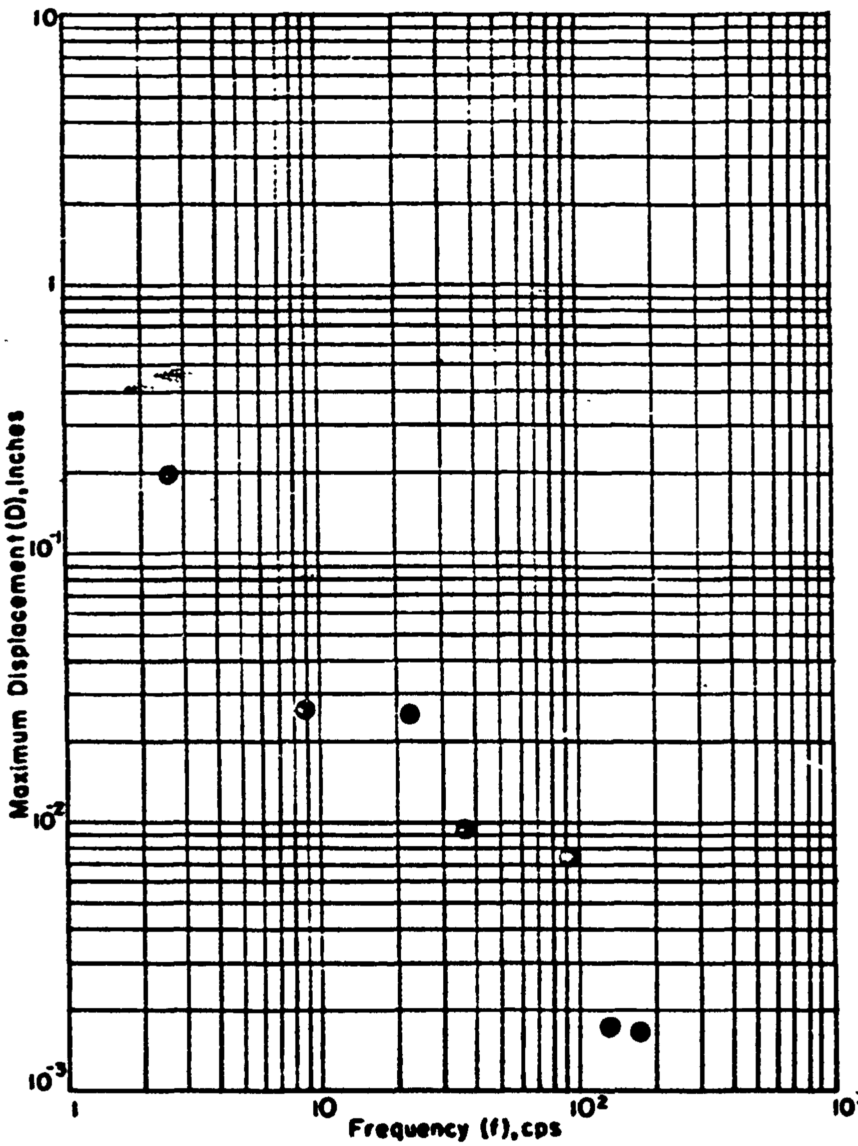

Figure 20 Displacement shock spectrum, radial direction; Shot Stokes, Gage 3, 33-psi overpressure, surface.

component. The displacements were two to three times higher for the vertical component than for the radial component at the low frequencies.

The scatter of data became more pronounced for the velocity and acceleration spectra as expected. Here again, however, certain trends were established. For the conditions of the tests it was evident that for the vertical component the values of the velocity reached

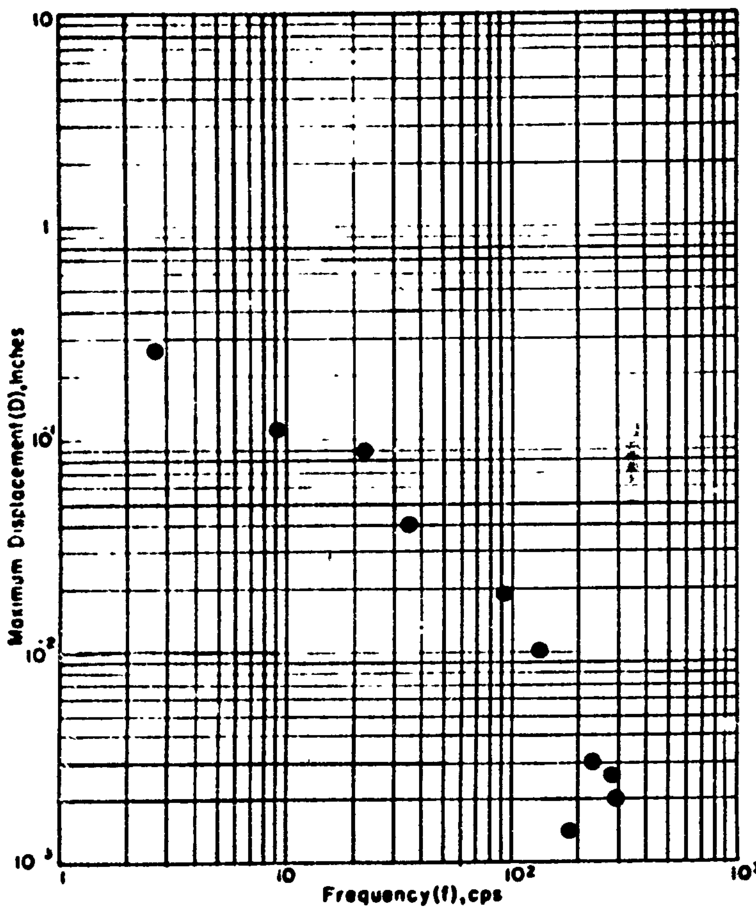

Figure 21 Displacement shock spectrum, radial direction; Shot Charleston, Gage 5, 20-psi overpressure, surface.

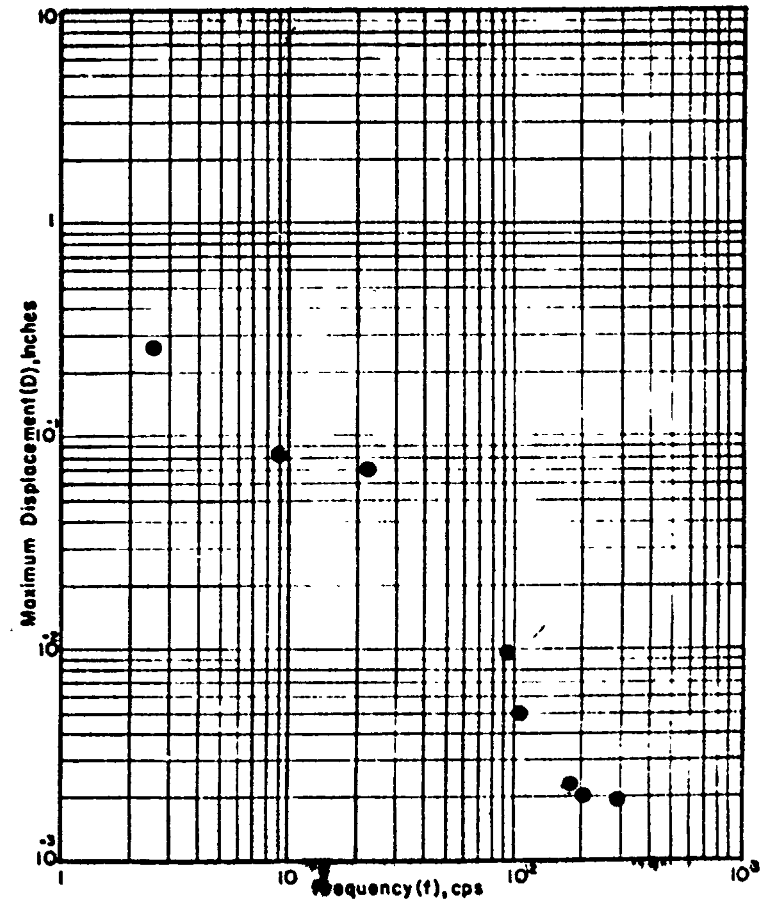

Figure 22 Displacement shock spectrum, radial direction; Shot Charleston, Gage 9, 18-psi overpressure, surface.

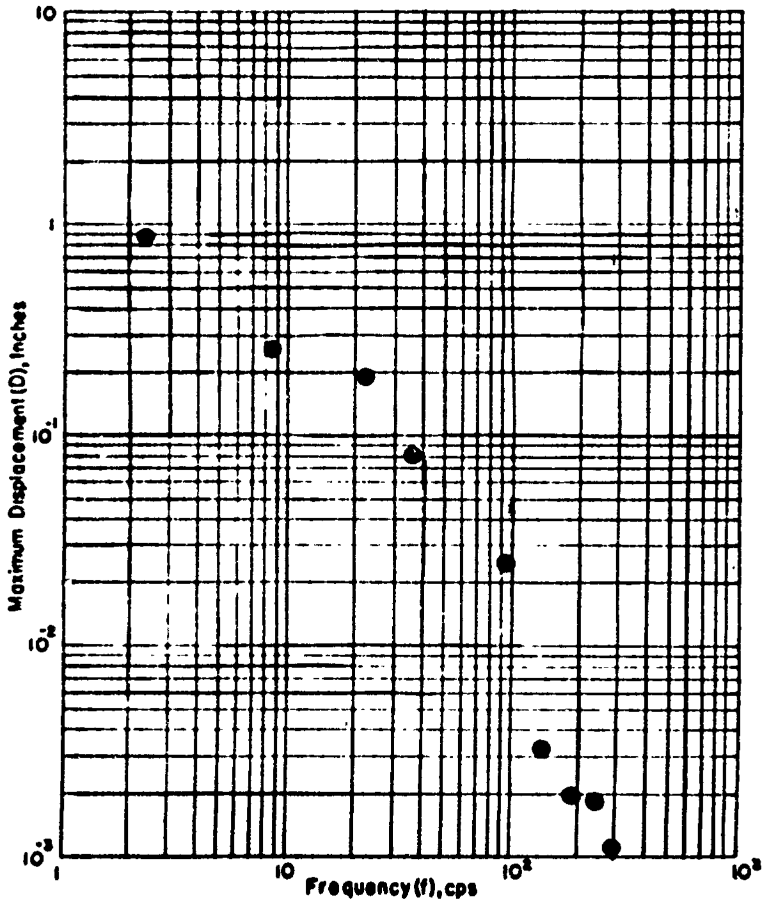

Figure 23 Displacement shock spectrum, radial direction; Shot Charleston, Gage 11, 15-psi overpressure, surface.

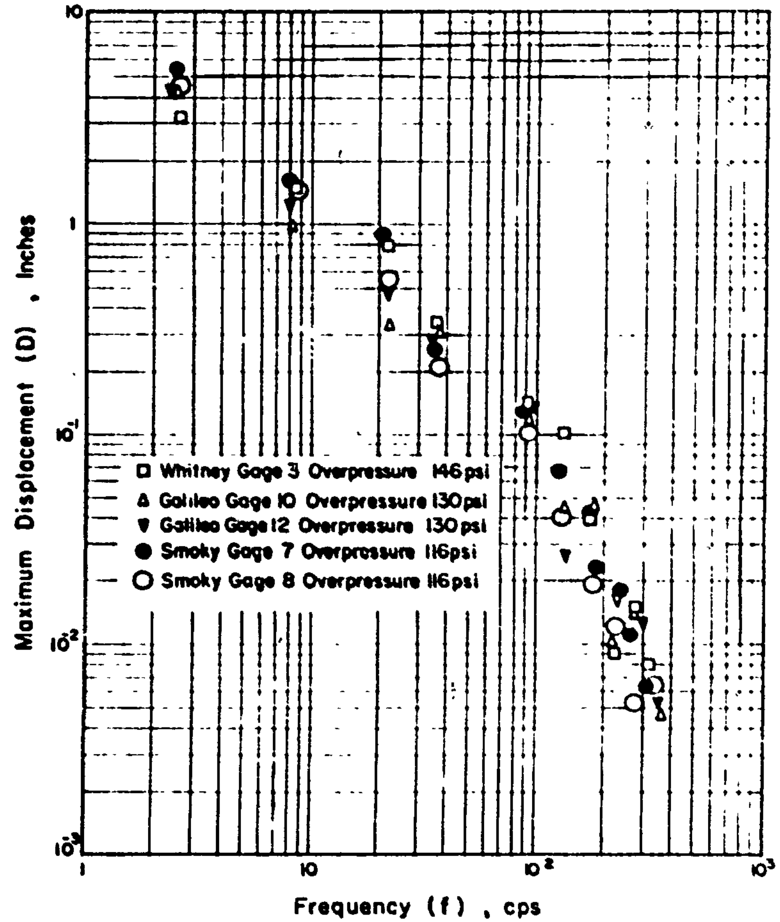

Figure 24 Displacement shock spectrum, vertical direction; Shots Whitney, Galileo and Smoky, surface.

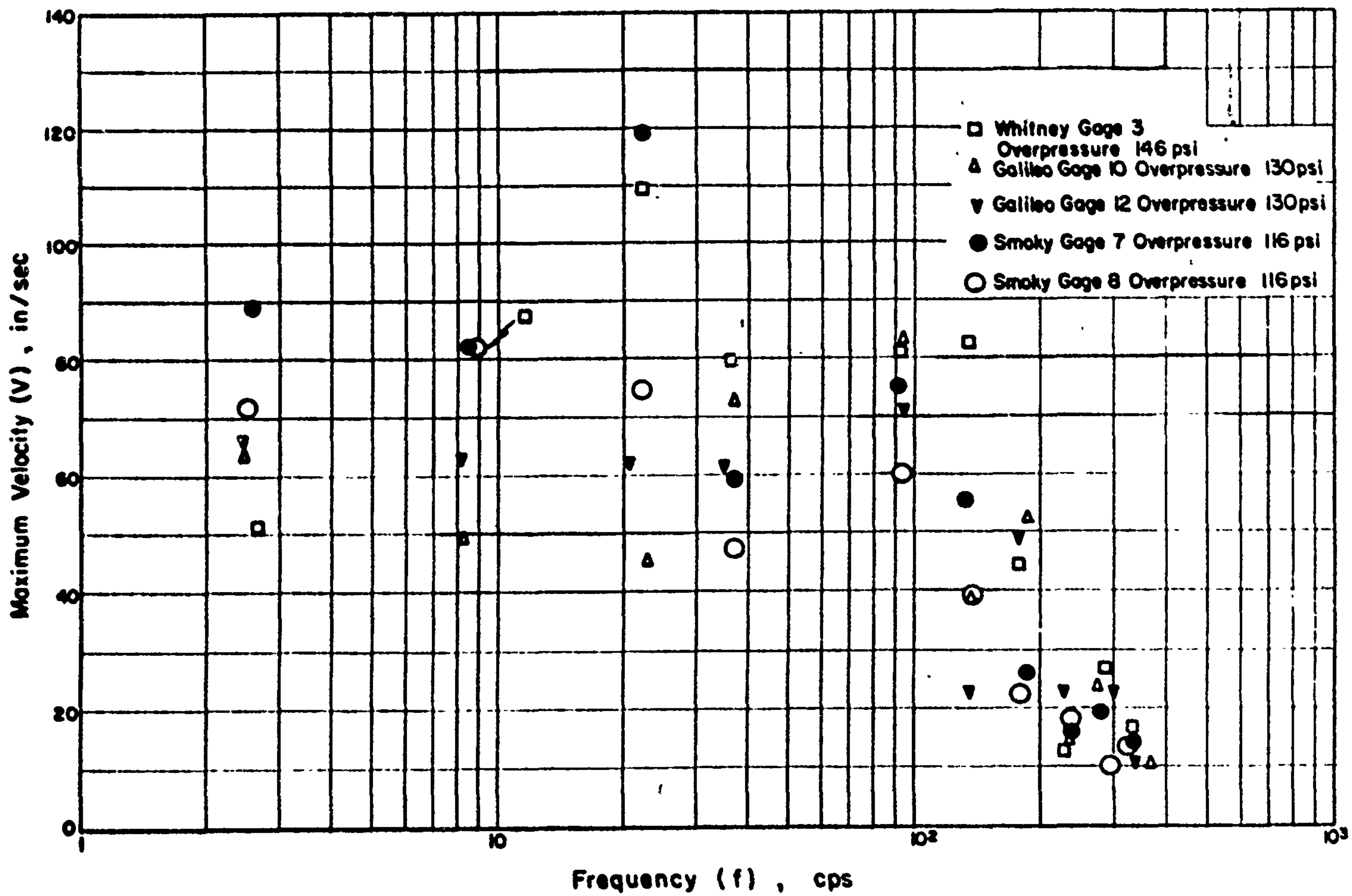

Figure 25 Velocity spectrum, vertical direction; Shots Whitney, Galileo and Smoky.

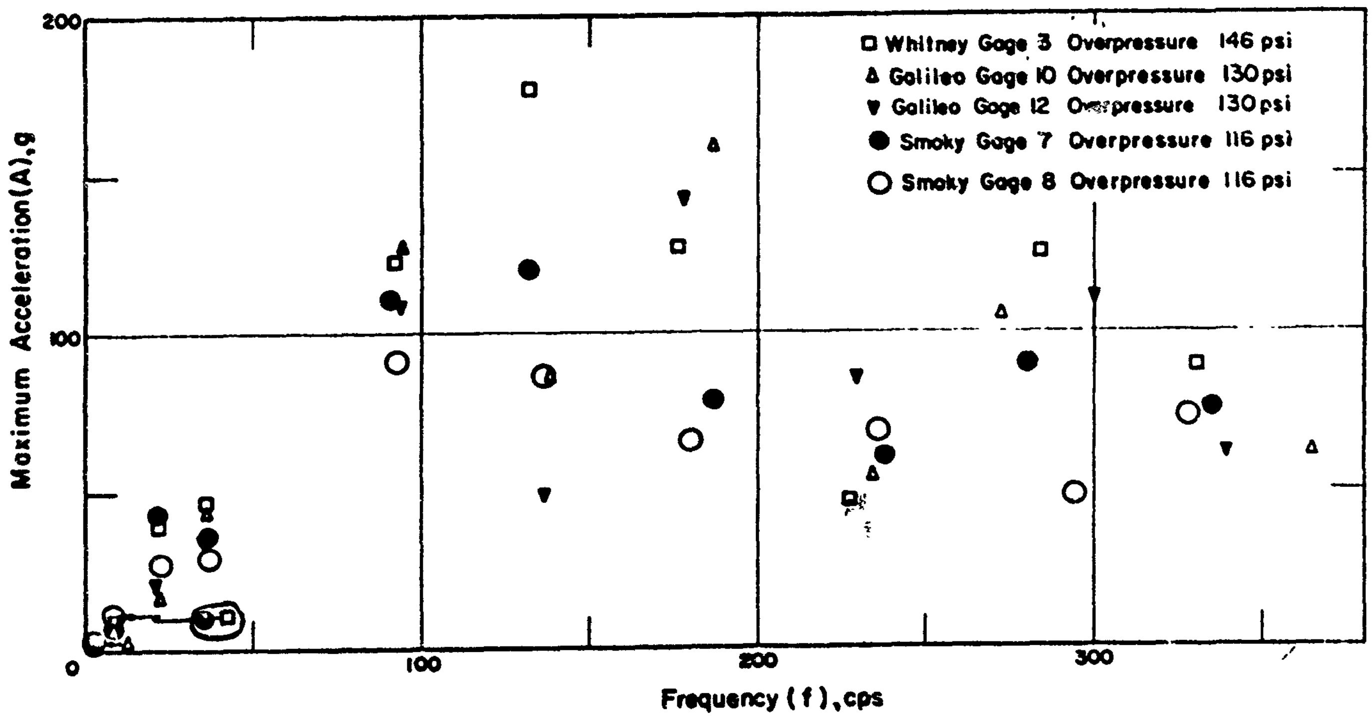

Figure 26 Acceleration spectrum, vertical direction; Shots Whitney, Galileo and Smoky.

a maximum at about 20 cps (Figure 25), and the accelerations peak between 140 to 160 cps (Figure 26). The radial component of the velocity indicated no clear peak (Figure 30), while the acceleration generally increased with frequency, (Figure 31). No generalizations are stated or implied by the foregoing remarks.

For single air blast pulses it can be shown that the maximum value of the acceleration

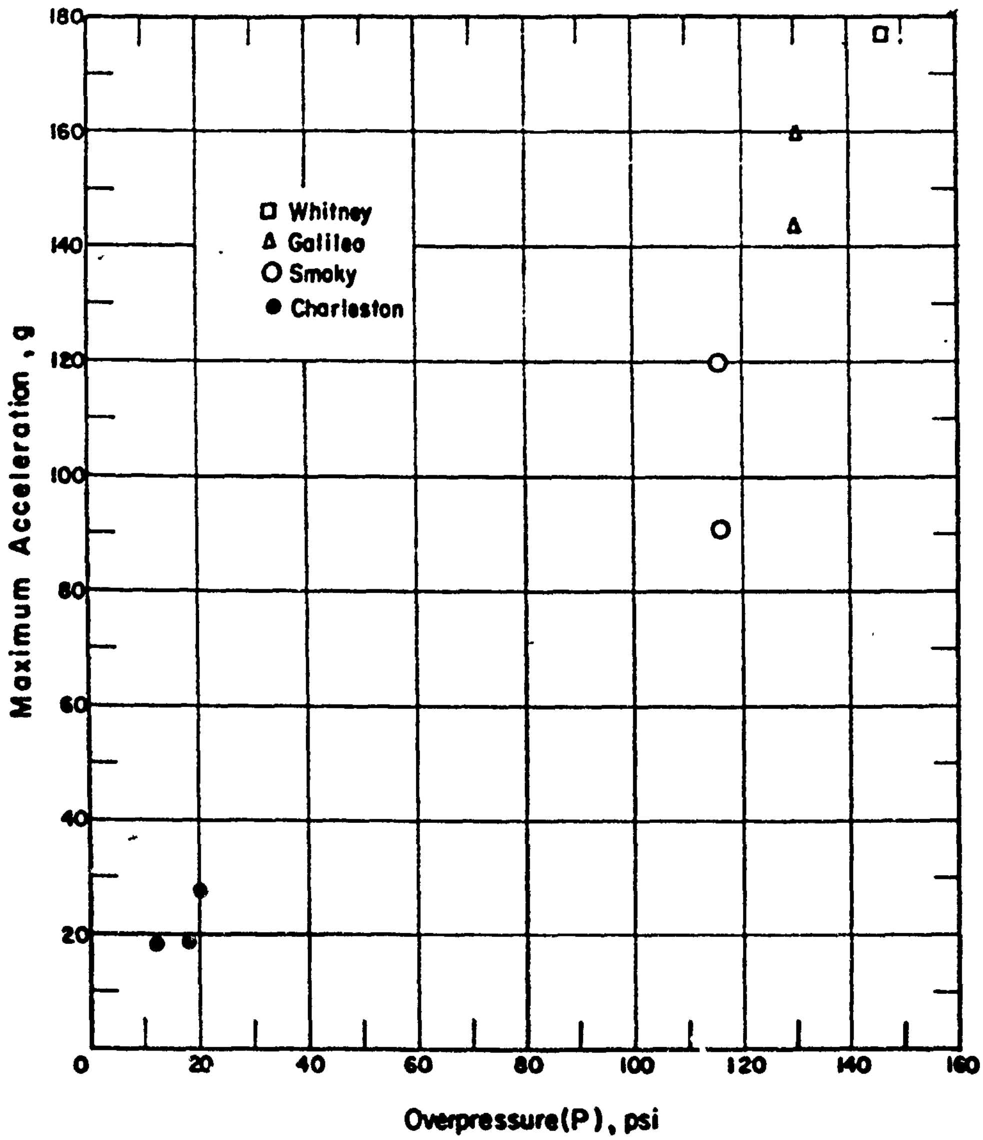

Figure 27 Maximum acceleration versus overpressure, vertical direction; Shots Whitney, Galileo, Smoky, and Charleston.

response is related to the rise time and the magnitude of the pulse. Assuming the rise time for all the shocks to be about the same, and that the magnitude of the shock is proportional to the overpressure, one would expect to find a linear relationship between peak acceleration and overpressure. That this is approximately true for the vertical motion is demonstrated in Figure 27.

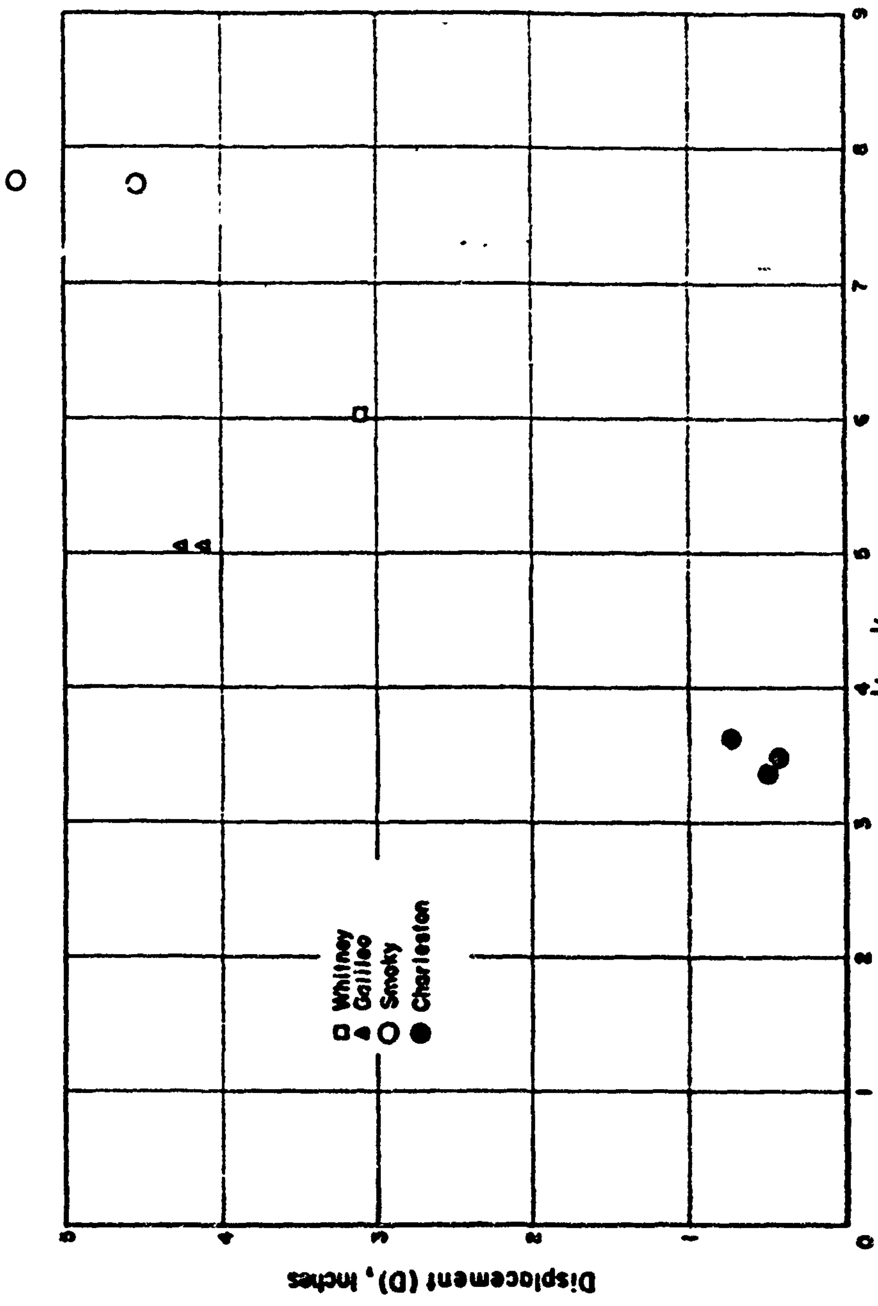

Figure 28 Displacement at 3 cps versus (Overpressure)$^{1/6}$ (Yield)$^{1/3}$, vertical direction. Overpressure: p - psi. Yield: W - kilotons.

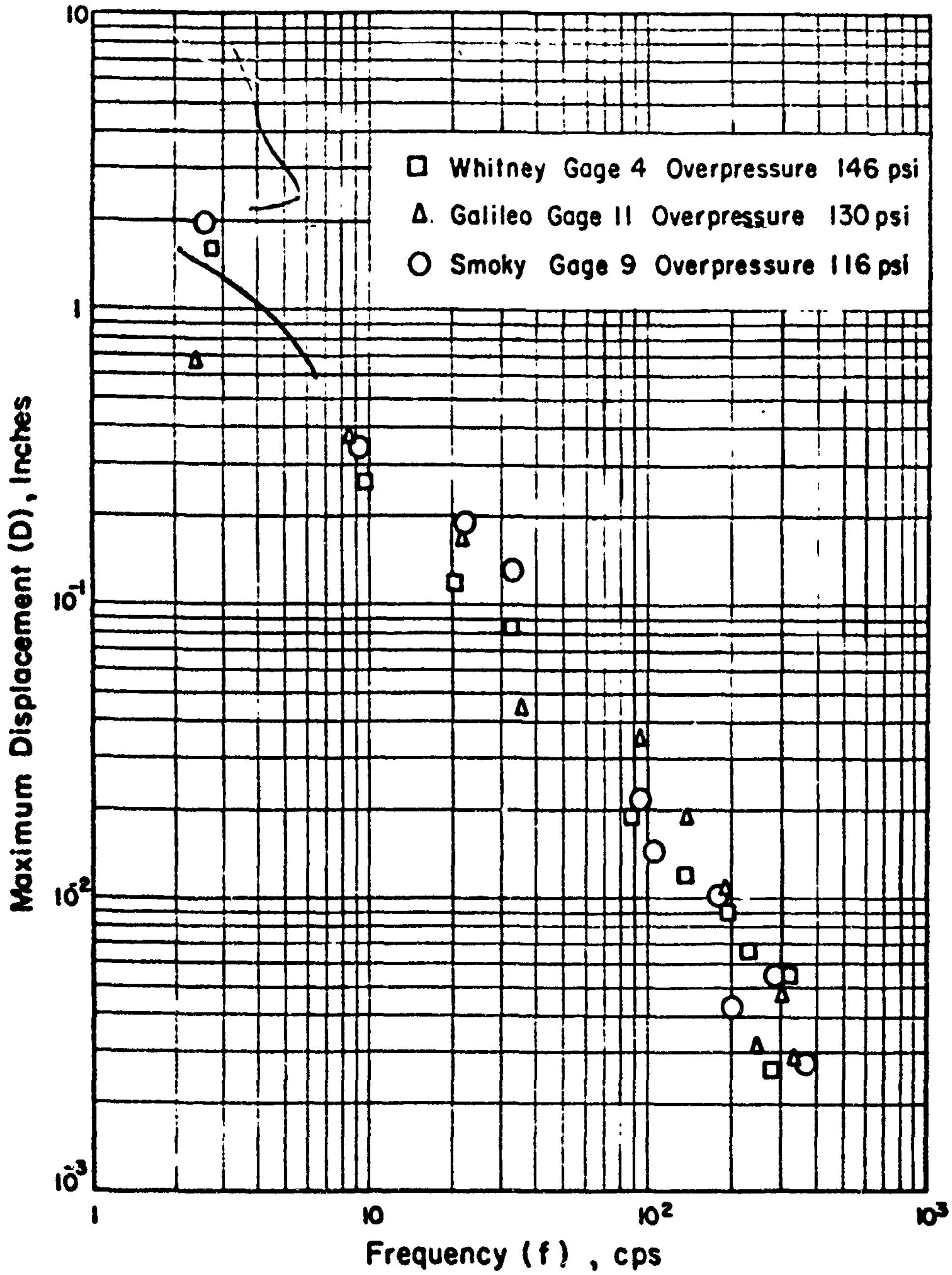

Figure 29 Displacement shock spectrum, radial direction; Shots Whitney, Galileo and Smoky, surface.

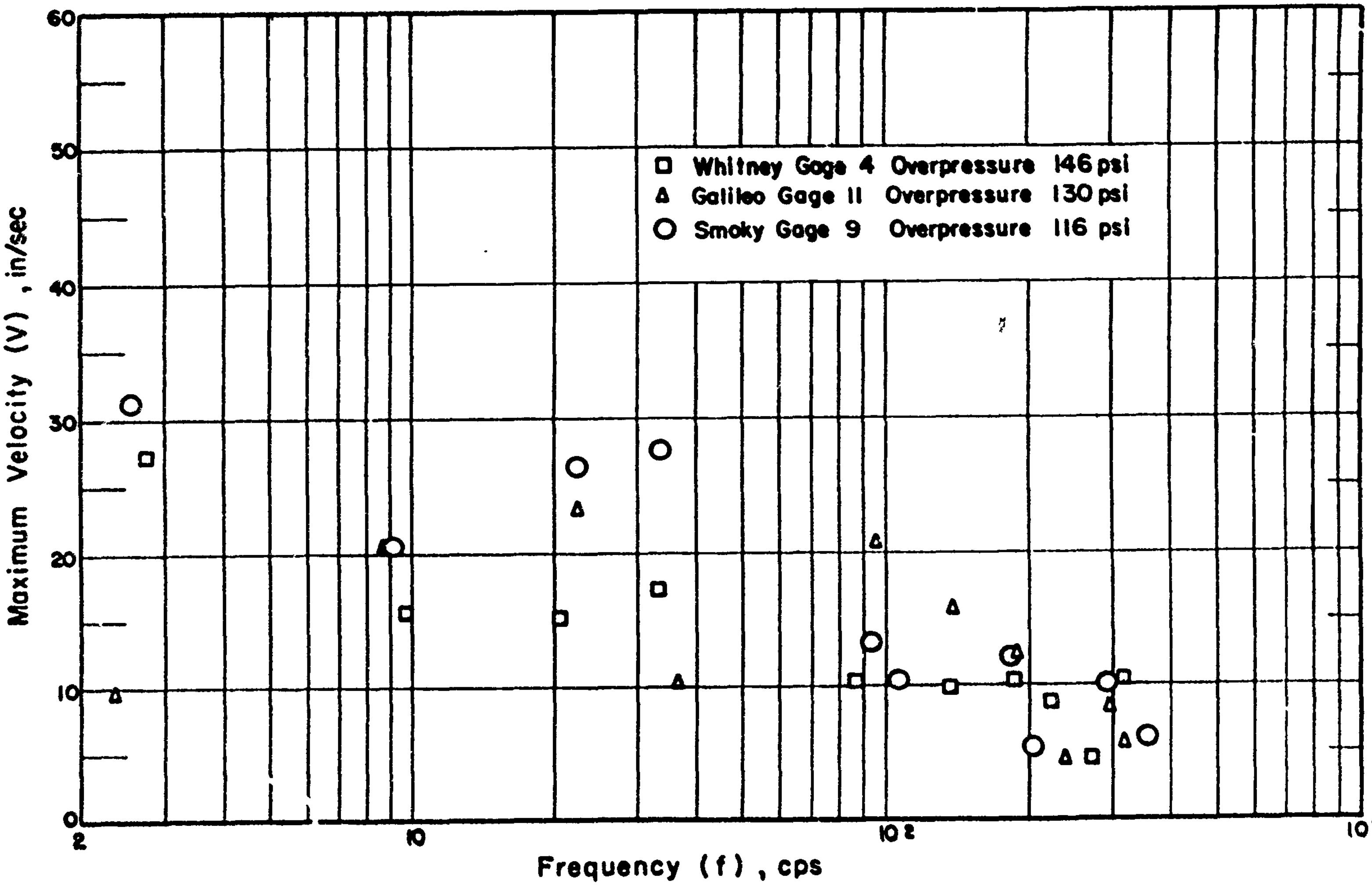

Figure 30 Velocity spectrum, radial direction; Shots Whitney, Galileo and Smoky.

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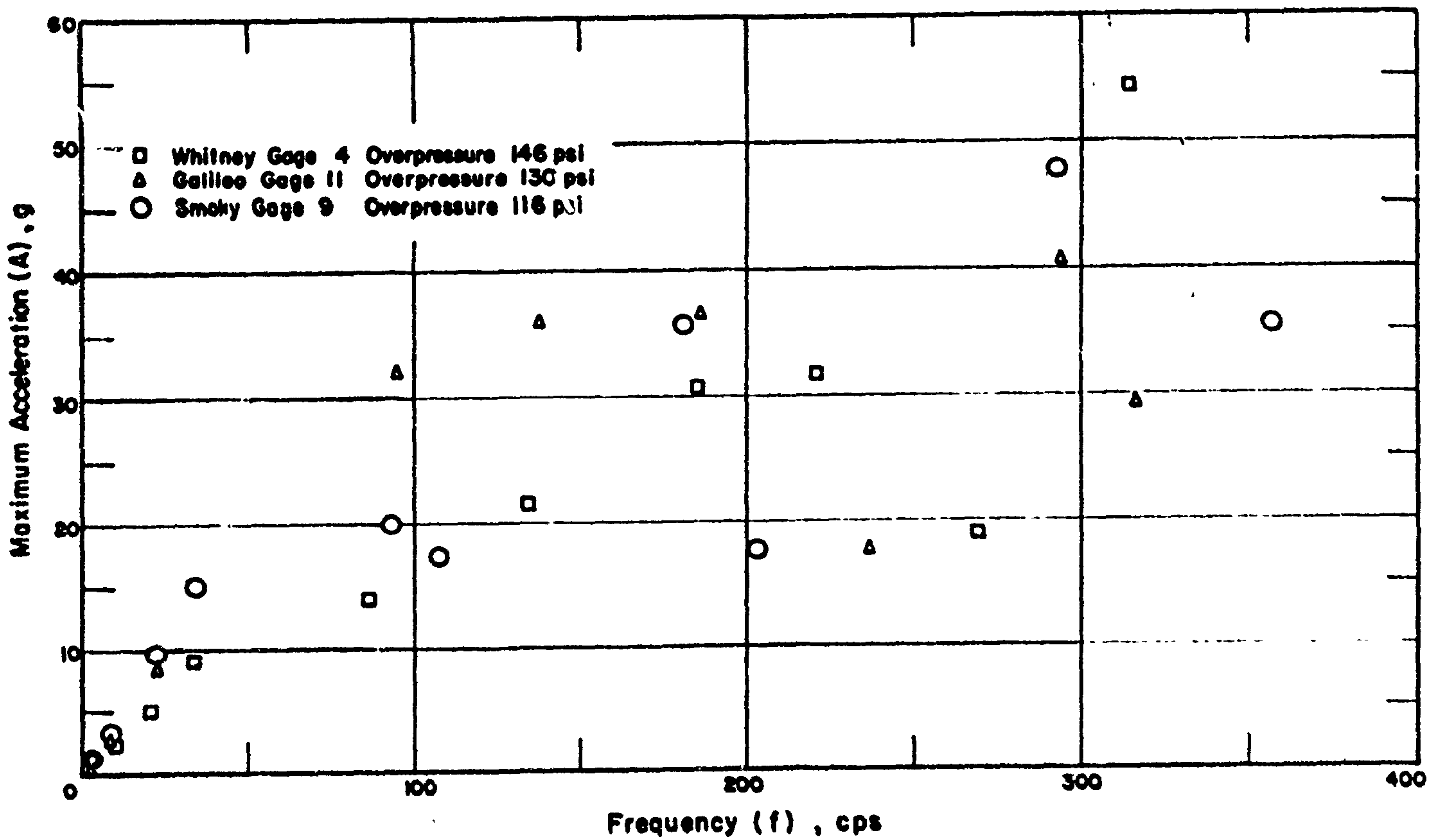

Figure 31 Acceleration spectrum, radial direction: Shots Whitney, Galileo and Smoky.

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This correlation is less apparent for the radial component (Figure 32). It is known that for single pulse type inputs, the initial slope of the acceleration shock spectrum is proportional to the total impulse. It would therefore be expected that the displacement spectra for a low frequency (approaching zero) would be proportional to the total impulse. To investigate this possibility, it has been assumed that the total ground impulse is proportional to the one-overpressure impulse which can be shown to be proportional to $p^{1/6}$ $W^{1/3}$, where p is the overpressure and W is the yield. The indecisive correlation is shown in Figures 28 and 33.

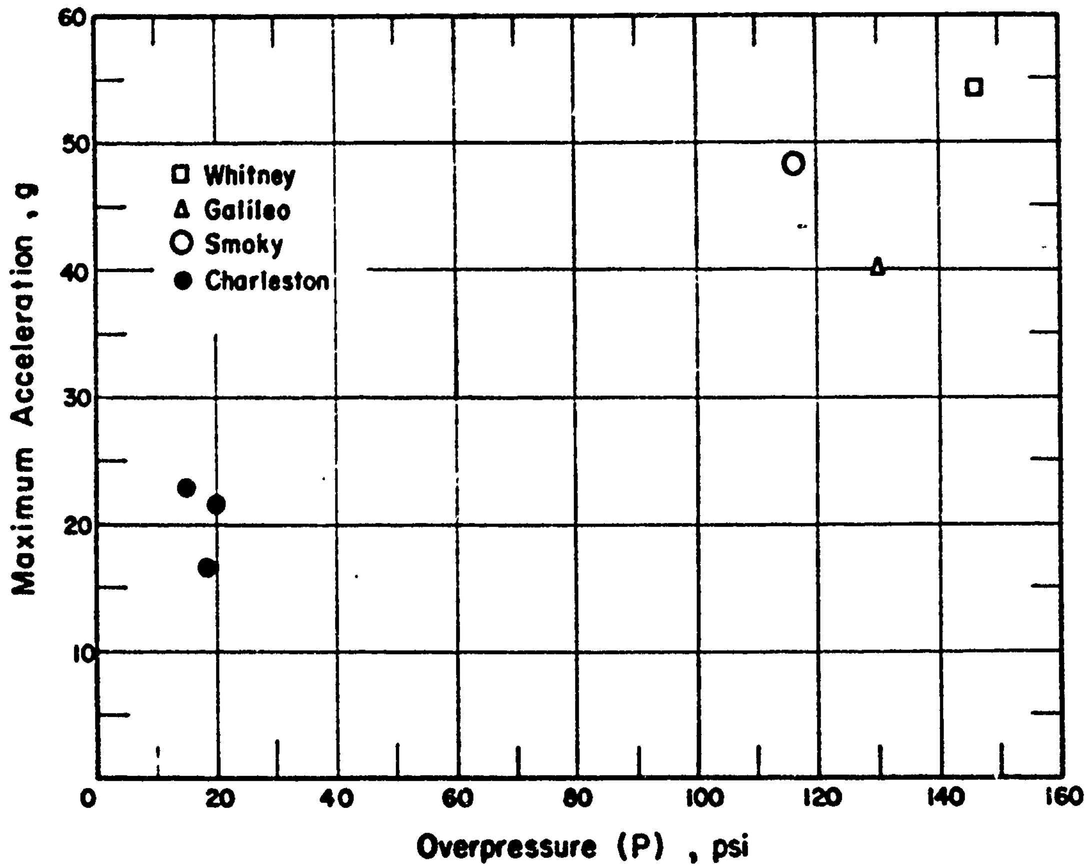

Figure 32 Maximum acceleration versus overpressure, radial direction; Shots Whitney, Galileo, Smoky, and Charleston.

CONCLUSIONS

The records obtained fulfilled the objectives of the project, i.e., the displacement shock spectra of ground shocks produced by nuclear devices was measured directly. The data appears to be quite reliable and is in a form that will enable a designer of structures to readily estimate stress and displacement responses (within the elastic limit) of structures, particularly those possessing low natural frequencies and a small amount of damping

RECOMMENDATIONS

Reed-type gages should be used as primary instruments for measuring ground shock characteristics for a wide variety of soil, yield and other conditions. Whenever possible,

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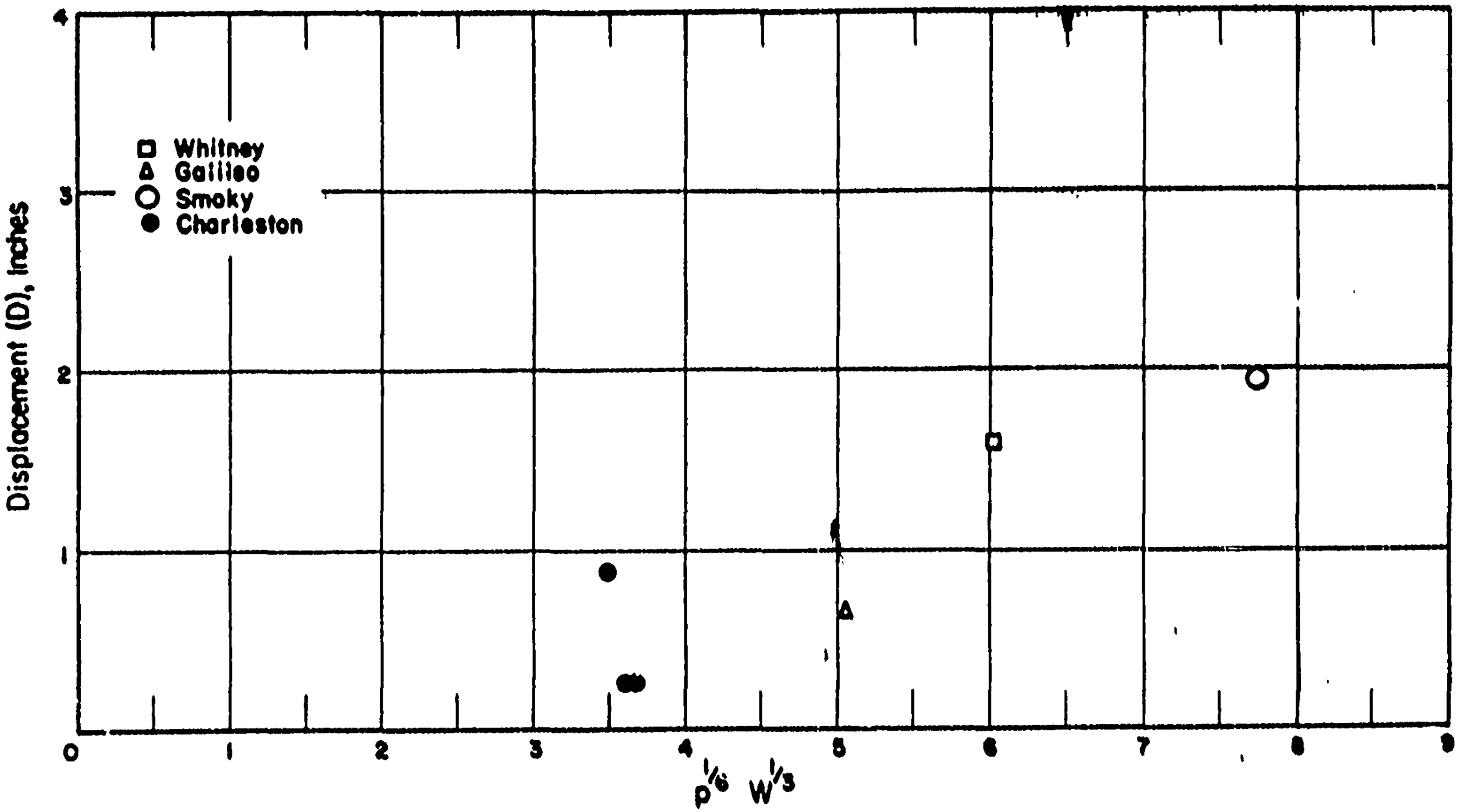

Figure 33 Displacement at 3 cps versus (Overpressure)$^{1/6}$ (Yield)$^{1/3}$, radial direction. Overpressure: p - psi. Yield: W - kilotons.

[redacted]

correlations of shock-spectra measurements should be made with analyzed records of acceleration measurements.

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2. Y. C. Fung; "On the Safety of Structures Against Ground Shocks"; GM-TR-191, The Ramo-Wooldridge Corporation; 15 June 1957.

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