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Operation
NOUGAT
SHOT HARD HAT

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PROJECT OFFICERS REPORT—PROJECT 3.12

DISPLACEMENT SPECTRUM MEASUREMENTS (U)

M. V. Barton, Project Manager
F. A. Pieper, Project Officer

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Redondo Beach, California

Issuance Date: May 17, 1963

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DEPARTMENT OF DEFENSE
WASHINGTON 25, D.C.

ABSTRACT

Twenty-one reed gages were installed for the Hard Hat event by Space Technology Laboratories, Inc. (STL) for radial (horizontal) and vertical displacement shock spectrum measurements on the Hard Hat event. Thirteen gages were installed in the tunnel liner structures of Project 3.1. Seven gages were installed in the unlined access tunnel floor. One gage was installed on the surface at a radial distance of 1,340 feet from Hard Hat zero point.

Damage in the drift nearest the detonation, although expected to be large, was so severe that the drift was not opened and gage recovery at that range was therefore impossible. Fifteen of the 21 gages installed were recovered and of these, 12 yielded usable records. The three gages which yielded no information were damaged by collapse or partial collapse of the tunnel and structures in which they were placed.

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DISPLACEMENT SPECTRUM MEASUREMENTS

INTRODUCTION

The Hard Hat event involved the detonation of a nominal 5-kt nuclear device at a depth of 950 feet in the granite of Area 15 at the Nevada Test Site. The primary purpose was to obtain tunnel liner structures response data.

The tunnel liner structures program presented an opportunity to make displacement spectrum measurements under three directly related conditions.

1. In the transmitting medium (modified free-field).
2. In structures close-coupled to the transmitting medium.
3. In structures separated from the transmitting medium by various shock absorbing materials.

Objective. The objective of this project was to measure the displacement response spectrum of ground and structure motion at a series of discrete frequencies between 3 and 300 cps. The displacement spectrum is a plot of peak relative displacement versus frequency of a set of several linear fixed-frequency oscillators (of single degree of freedom) resulting from the motion of the ground or structure.

Background. The use of self-contained mechanical reed gages capable of measuring the displacement shock spectrum in any one direction provided an indication of the characteristics of blast induced and ground-transmitted ground shock under conditions of low-yield loading during Operation Plumbbob (Reference 1). Additional measurements, free field and in structures, were made for high-and low-yield loadings during Operation Hardtack at the Pacific Proving Ground (Reference 2). Surface measurements of the shock spectrum generated by underground nuclear detonations were made during Operation Hardtack, Phase II, and Operation Nougat (Reference 3) at the Nevada Test Site.

Measurements of the surface ground shock spectrum were obtained during the 20-ton trial at the Suffield Experimental Station (SES), Ralston, Alberta, Canada, and both the surface and near surface spectrum resulting from the 100-ton trial at SES in 1961 (Reference 4).

These data have been utilized in preparing the environmental information considered essential for the design of missile systems hard bases for the Air Force Ballistic Systems Division (AFBSD) and in theoretical studies of scaling effects.

Theory. The response of any linear structure can be represented as the sum of its principal mode responses as

$$u(t, x, y, z) = \sum_n q_n (t) \phi_n (x, y, z) \qquad (1)$$

where u = displacement relative to the undeformed position of the body

q_n = generalized coordinate of the n^{th} mode

ϕ_n = mode shape of the n^{th} mode

An upper bound of the response is obtained by assuming that all modes reach maximum values at the same time. Thus,

$$u_{max} (x, y, z) = \sum_n \left| q_{n_{max}} \phi_n (x, y, z) \right| \qquad (2)$$

If a structure is attached to the ground which is subjected to an acceleration pulse, u will be the displacement relative to the ground and it can be shown that

$$\ddot{q}_n + 2 \varepsilon \omega_n \dot{q}_n + \omega_n^2 q_n = - \gamma_n a(t) \qquad (3)$$

in which ε = damping ratio

ω_n = frequency of the n^{th} mode

γ_n = modal participation factor of the n^{th} mode

$= \int \rho \phi_n \, dv \Big/ \int \rho \phi_n^2 \, dv$

ρ = mass distribution per unit volume

a = acceleration of the ground

Assume now an ideal single-degree-of-freedom system such as a point mass on a weightless cantilever spring. The equation of motion for this system is

$$\ddot{Q} + 2\zeta\omega\dot{Q} + \omega^2 Q = - a(t) \qquad (4)$$

The reed shock gages, with appropriate corrections to account for mass distribution and stylus location, read directly the peak relative displacements, Q, which are solutions of Equation 4. The frequency spectrum of the peak displacements of the masses relative to the base which is accelerated is called the displacement spectrum. That is

$$D(\omega) = \max_{0 \leq t \leq T} \left[Q(\omega,t) \right] \qquad (5)$$

where the time interval (0, T) represents the time of interest.

Noting the similarity of Equations 3 and 4 it can be seen that, knowing the displacement spectrum, the modal response of a structure having the same damping as the gage is given by

$$q_{n_{\max}} = \gamma_n D(\omega_n) \qquad (6)$$

The upper bound of the response is given by

$$u_{\max} \leq \sum_n \left| \gamma_n D(\omega_n) \phi_n \right| \qquad (7)$$

according to Equation 2.

The velocity spectrum is defined as

$$V(\omega) = \omega D(\omega) \tag{8}$$

This is a pseudovelocity in that it has units of velocity but represents neither the velocity relative to the moving base nor an absolute velocity. It is useful, however, in the determination of an upper bound of strain energy in a structure.

The acceleration spectrum, defined as

$$A(\omega) = \omega^2 D(\omega) \tag{9}$$

is truly the peak absolute acceleration. Its magnitude could be read by means of an accelerometer on each reed. Consequently,

$$A(\omega) = \max_{0 \leq t \leq T} \left[\ddot{Q}(\omega, t) + a(t) \right]. \tag{10}$$

PROCEDURE

Operations. Project activities at the site consisted of installation and adjustment of gages and record plates and subsequent postshot recovery operations.

Instrumentation. Gages used in this test were the STL designed reed gages previously used to measure shock spectra in the nuclear tests in Nevada and Eniwetok. The gages consist of ten masses on cantilever springs or reeds, mounted on a rigid base. The masses and spring constants of the ten reeds are so designed that their natural frequencies cover the range between 3 and 300 cps. Nominal frequencies are 3, 10, 20, 40, 80, 120, 160, 200, 250, and 300 cps.

The masses, which move in one plane, have scribers in contact with a polished metal record plate. A thin layer of lamp black is deposited on the record prior to final installation by smoking it with a candle. As the reeds vibrate after being subjected to a shock, the maximum displacement of each mass is recorded on the smoked plate by the scribers. These displacements are measured and equivalent values for the mass motion are plotted against the natural frequencies of the reeds to obtain the shock spectrum curves for the various installations.

Figure 1 shows (from left to right) the 3-, 40-, and 20-cycle reeds with the record plate inserted. Figure 2 shows the remaining reeds on the opposite side of the gage. The gages were installed in protective canisters, horizontally as shown in Figure 3, or vertically as shown in Figure 4.

Seven gages were installed in the access tunnel floor, as shown in Figure 5. Thirteen gages were installed in the tunnel liner structures, as shown in Figures 6, 7, 8, 9, and 10. Additionally, one gage was installed on the surface. The gages were located and oriented as follows:

Access Tunnel Locations	Gage Number and Orientation
A drift (250 ft. radial distance to zero)	27-Vertical (V)
B drift (340 ft. radial distance to zero)	2-V and 24 Radial (R)
C drift (460 ft. radial distance to zero)	*26-V and *20-R
725 ft. radial distance to zero	*16-V and *25-R

Structure Locations

Structure Designation	Radial Distance to Zero	Structure Description	Gage Number and Orientation
A 3 a	250 ft.	12" Concrete against rock	23-R
A 3 b	250 ft.	12" Concrete w/9" foam	18-R
A 3 c	250 ft.	8" Concrete w/24" foam	13-R
B 3 a	340 ft.	12" Concrete against rock	19-R and 22-V
B 3 b	340 ft.	12" Concrete w/9" foam	*12-R and *5-V
B 3 c	340 ft.	8" Concrete w/24" foam	*15-R
B 3 d	340 ft.	12" Concrete w/cinders	6-R
C 3 a	460 ft.	12" Concrete against rock	*4-R

(Continued)

Structure Designation	Radial Distance to Zero	Structure Description	Gage Number and Orientation
C 3 b	460 ft.	12" Concrete w/ 5" foam	*7-R
C 3 c	460 ft.	8" Concrete w/24" foam	*21-R
C 4 b	460 ft.	Steel Set/Stl. Lag. w/5" foam	*8-R

Note: The floor of the access tunnel was approximately 80 feet above Hard Hat zero.

Surface Location. *Gage No. 1, oriented vertically, 1340 feet radial distance to zero (996 feet horizontal distance to zero, 900 feet vertical distance to zero). NTS coordinates N 902,159.97, E 677,795.79 Elevation 5073.97.

* Indicates those gages from which usable records were recovered. The remaining gages and/or records were a total loss or were severely damaged.

RESULTS

The results are presented in Table 1 , Frequency-Displacement Data. Figures 15 through 26 are plots of the reduced data on triaxial graph paper such that the maximum relative displacement of the mass, the pseudovelocity , and the absolute acceleration are indicated for each frequency.

Although the reed gage was designed to obtain information in a ground shock environment produced by an air overpressure, the gage behaved very well in the strong direct ground shock environment of this test. Due to the high shock levels encountered in the test, many of the structures collapsed or damage was so severe that gages were lost, destroyed, or records obliterated. Of those 12 gages which yielded records, some reeds were overranged and went off scale. In a few instances recording styluses were bent or skipped. Generally, however, the records reported herein were clear and presented few data reduction problems.

It is believed that the displacement values given in Table 1 are within 20 percent of those of the true shock spectrum.

DISCUSSION

As may be noted from the frequency displacement data, the majority of the displacements at the lower frequencies (3, 10, and 20) were beyond the recording range of the gages.

The canisters and gages installed in the access tunnel floor at B drift were permanently displaced approximately four feet vertically and were severely damaged, as shown in Figures 11, 12, 13, and 14.

Observation of the instrumentation schedule, which indicates those gages that gave readings and those that failed due to excessive input, revealed no unexpected results. All gages at the A drift, 250 feet from the burst, failed. At the B drifts, 340 feet from the burst, those protected by a reinforced concrete liner backed by foam yielded some results, while those unprotected or protected by a reinforced concrete liner against rock, or backed by cinders, failed. At greater distances, readings were obtained from all gages. From these facts alone, it appears that foam backing for a structure offers some protection and is greater than that provided by a cinder backing. However, visual inspection of the postshot structures at the B drift demonstrates that a thick foam is much more effective protection than a thin one, and no difference could be observed in the extent of damage to the cinder backed and thin foam-backed structure (Reference 5). Some feeling for the relative protection offered by cinders and thin foam can be gained from observation of two steel liners at C drift. A steel liner backed with cinders in that location deformed more than a steel liner backed by foam.

Figures 27 thru 29 are presented for the purpose of making more detailed observations. As can be seen from Figure 27, the transmission of shock through a foam-backed structure seems to be independent of the thickness of foam in a light damage environment. The fact that the thin foam-backed structure, B3b, was severely damaged while damage to B3c was negligible may be due to the lower frequency components passed through the thinner foam (see Figure 28). An anomaly seems to be present in that the radial shock in an unlined tunnel is no more severe than that seen in the foam-protected structures at the same range (see Figure 27). This is belied by the fact that the radial gage at a closer range, B drift, in the access tunnel failed completely, while data was obtained from the radial gages in the foam-protected structures at that range. Again, Figure 29 shows that the radial shock in the access tunnel at the C drift is lower than might be expected, based upon a comparison of the vertical and radial shock at this location, at 725 feet from the burst, and in a structure in the B drift.

CONCLUSIONS

Examination of the plotted data in Figures 15 through 29 and the results discussed above allows the following conclusions. These conclusions are valid for the high frequencies. Limited data obtained in the low frequency range does not allow definite conclusions to be drawn.

1) The objective of this program was attained insofar as collapse and severe damage to structures allowed reed gage data to be obtained. Twelve of the twenty-one gages installed yielded readable records, and shock spectra for these gages are shown in Figures 15 through 26.

2) The coupling was best between the rock and liner structure C3a (12-inch concrete without back-packing, cast against rock) as compared with the open access tunnel-free field evidenced by the higher accelerations shown in Figures 22 and 27.

3) The plastic foam used in the experiment protected the structure it surrounds by attenuating the shock transmitted from the free field. This is true at least at the intermediate and far ranges, Drifts B and C.

4) The plastic foam appeared more effective in attenuating shock than cinders.

5) Limited data obtained due to loss of gages in the severe damage region preclude the possibility of establishing even crude scaling relations.

TABLE 1 FREQUENCY-DISPLACEMENT DATA

Gage No. 1 Surface(1340 ft.)		Gage No. 16 Access Tunnel Floor (725 ft.)		Gage No. 25 Access Tunnel Floor (725 ft.)		Gage No. 26 Access Tunnel Floor (460 ft.)		Gage No. 20 Access Tunnel Floor (460 ft.)		Gage No. 21 C3c (460 ft.)	
Vertical		Vertical		Radial		Vertical		Radial		Radial	
F(cps)	D(inches)	F(cps)	D(in.)	F(cps)	D(in.)	F(cps)	D(in.)	F(cps)	D(in.)	F(cps)	D(in.)
3.2	NV	2.5	SM	3.01	3.54	2.97	RF	3.0	NV	2.9	NV
9.8	RF	9.8	0.830	10.0	1.35	10.3	NV	10.1	NV	10.0	1.34
23	0.201	23	0.588	22.2	0.944	21.8	NV	23	0.864	23	NV
48	0.032	50	0.214	48	0.473	47	0.677	49	0.318	49	NV
90	0.008	88	0.064	88	0.149	91	0.314	90	0.280	90	0.236
138	0.003	138	0.041	141	0.041	139	0.174	138	0.113	136	0.111
177	0	180	0.029	186	SM	179	0.164	181	0.023	182	0.058
215	0	222	0.025	226	0.014	224	0.074	221	0.017	220	0.028
262	0	261	0.020	270	0.010	276	0.044	254	0.032	256	0.019
288	0	286	0.016	300	0.010	298	RO	283	0.027	288	0.007

Notes:
1) Distances in parentheses after gage location indicate radial distance to zero.
2) Frequencies, F, are actual reed frequencies measured in the laboratory.
3) Displacements, D, are measured values after application of corrections for mass distribution of the reed and for stylus location.
4) In Table, NV means record not valid, reed went out of recording range; RF means reed failed; SM means stylus missed; and RO means record obscured.

TABLE 1 CONTINUED

Gage No. 7 C3b (460 ft.)		Gage No. 8 C4b (460 ft.)		Gage No. 4 C3a (460 ft.)		Gage No. 5 B3b (340 ft.)		Gage No. 12 B3b (340 ft.)		Gage No. 15 B3c (340 ft.)	
Radial		Radial		Radial		Vertical		Radial		Radial	
F(cps)	D(in.)	F(cps)	D(in.)	F(cps)	D(in.)	F(cps)	D(in.)	F(cps)	D(in.)	F(cps)	D(in.)
2.9	NV	3.1	RF	3.3	RF	2.8	RF	2.9	RF	3.0	RF
9.5	NV	10.1	NV	9.9	NV	10.0	SS	10.3	SS	10.0	NV
23	NV	23	0.961	23	NV	23	0.715	23	NV	22	NV
48	NV	49	RF	51	NV	50	SS	48	SS	49	0.692
90	0.140	91	0.199	91	NV	90	0.297	90	0.082	90	SS
138	0.121	137	0.109	138	NV	138	SS	137	0.180	136	SS
182	0.072	178	0.058	181	0.248	180	SS	180	0.128	178	0.043
216	0.033	221	0.038	221	0.149	221	0.061	215	0.091	218	0.062
262	0.014	254	0.015	262	RO	262	0.051	262	0.046	258	0.061
281	0.027	288	0.010	288	0.081	288	0.039	289	0.030	287	0.032

Notes:

1) Distances in parentheses after gage location indicate radial distance to zero.

2) Frequencies, F, are actual reed frequencies measured in the laboratory.

3) Displacements, D, are measured values after application of corrections for mass distribution of the reed and for stylus location.

4) In Table, NV means record not valid, reed went out of recording range; RF means reed failed; SM means stylus missed; RO means record obscured, and SS means stylus skipped, record not valid.

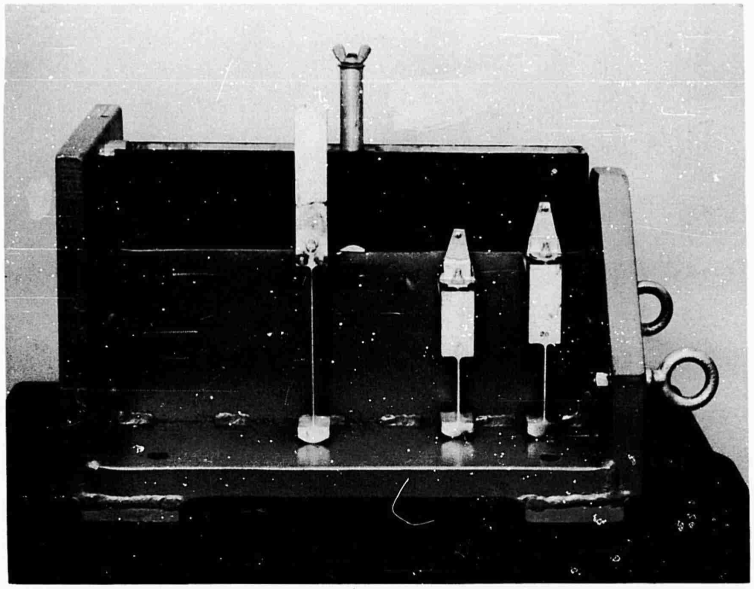

Figure 1 Reed gage, 3-, 40-, and 20-cycle reeds. (STL photo 71868-61)

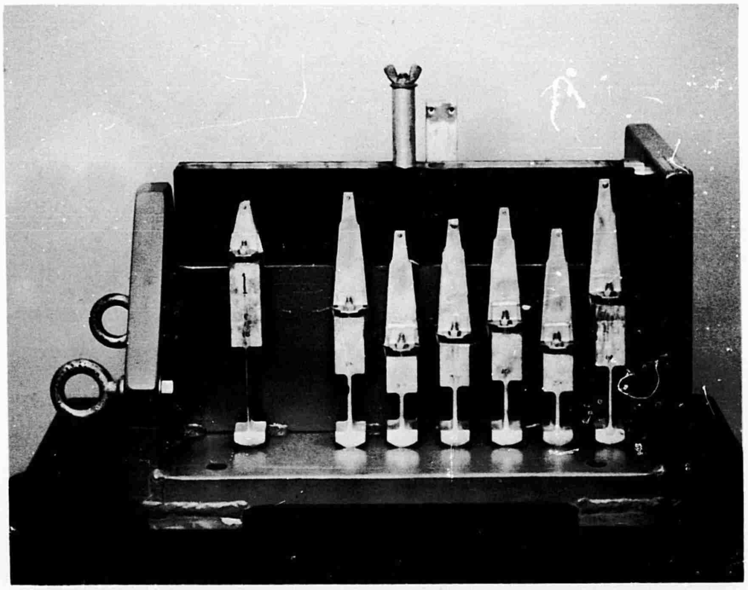

Figure 2 Reed gage, 10-, 120-, 300-, 200-, 160-, 250-, and 80-cycle reeds. (STL photo 71867-61)

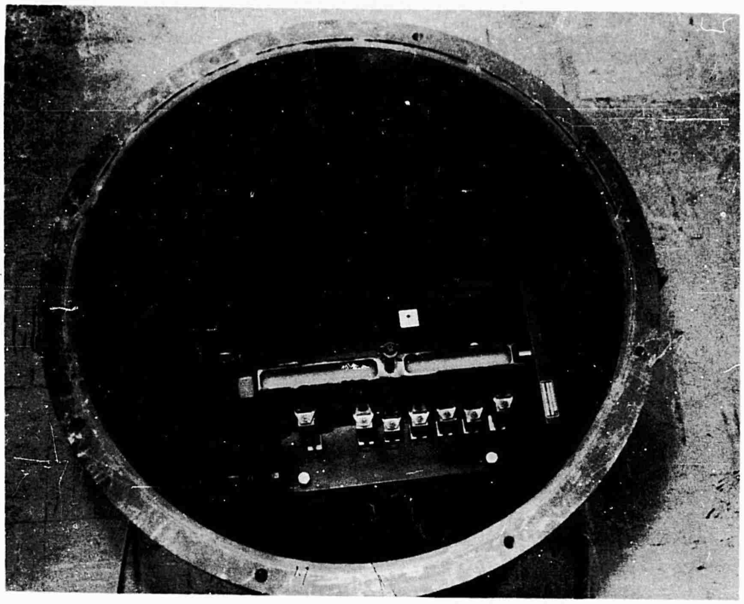

Figure 3 Gage installed horizontally (radially) in canister. (STL photo 71869-61)

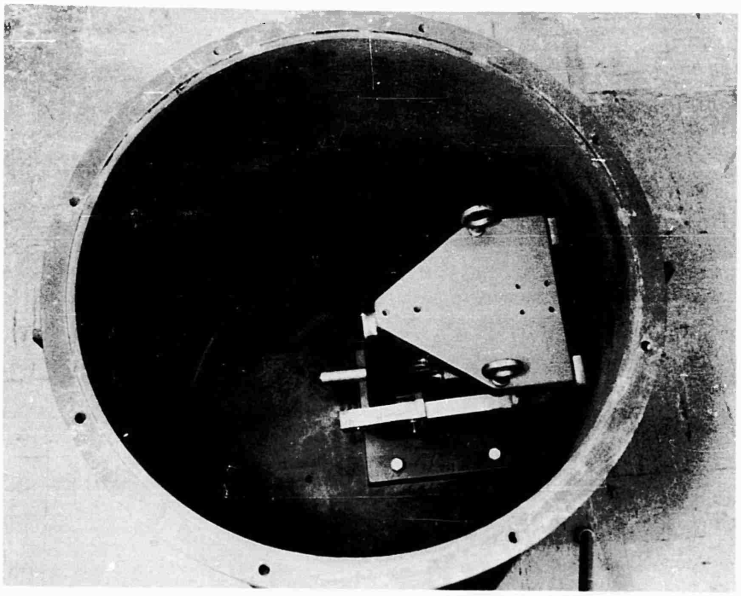

Figure 4 Gage installed vertically in canister. (STL photo 71870-61)

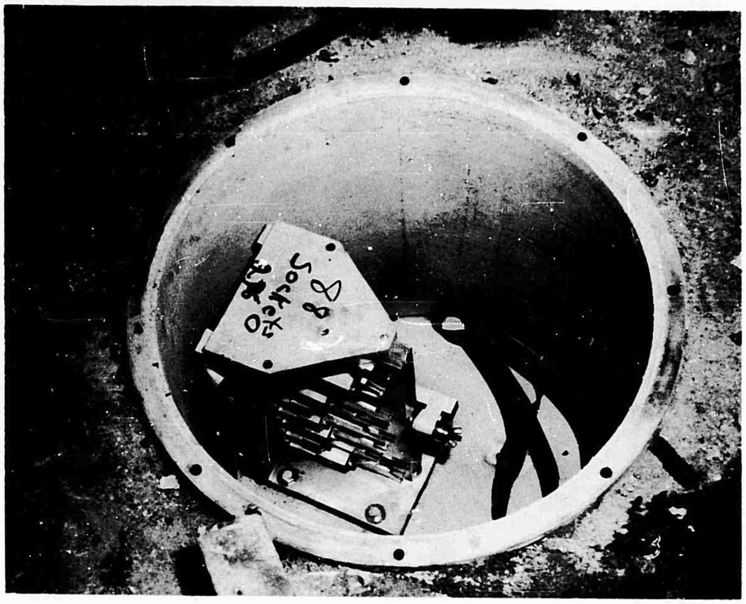

Figure 5 Gage and canister installed in access tunnel floor. (FCWT DASA 048 (NOU-083-02) NTS-62)

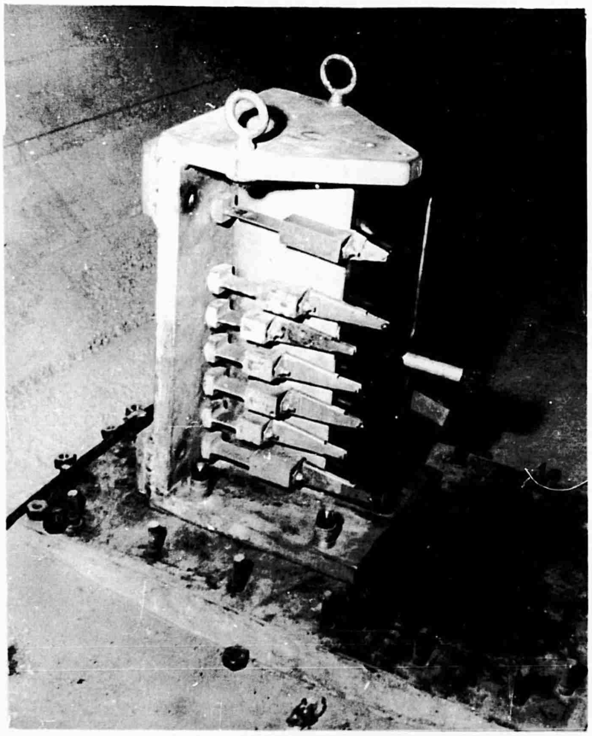

Figure 6 Gage installed vertically in liner structure B3b. (FCWT DASA 043 (NOU-032-05) NTS-62)

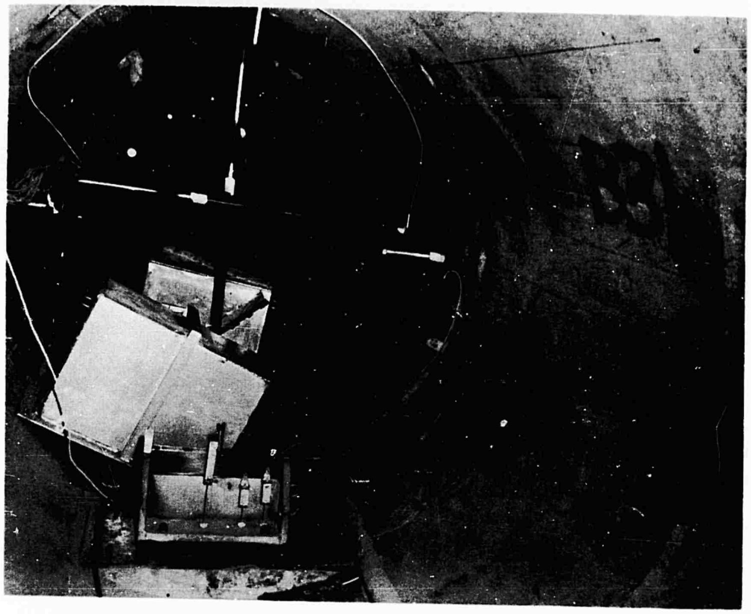

Figure 7 Gage installed radially in liner structure B3b. (FCWT DASA 048 (NOU-082-06) NTS-62)

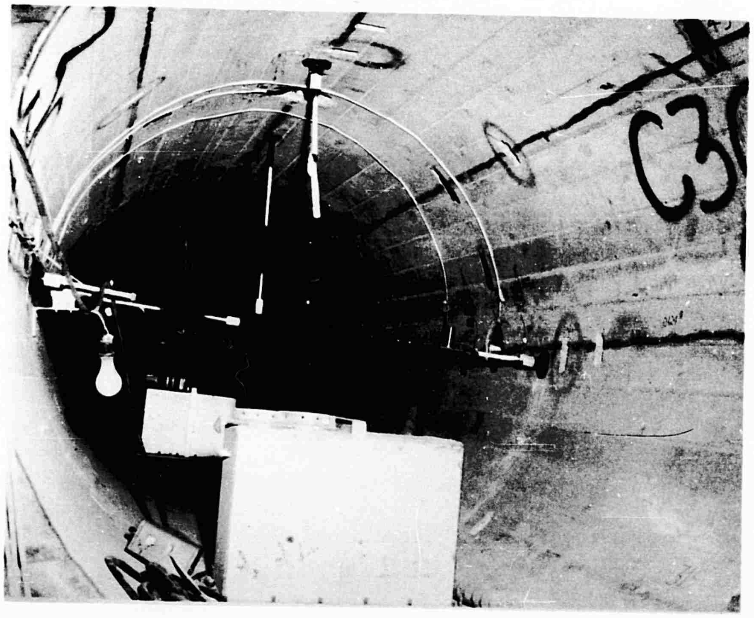

Figure 8 Covered radial gage in liner structure C3c. (FCWT DASA 048 (NOU-083-11) NTS-62)

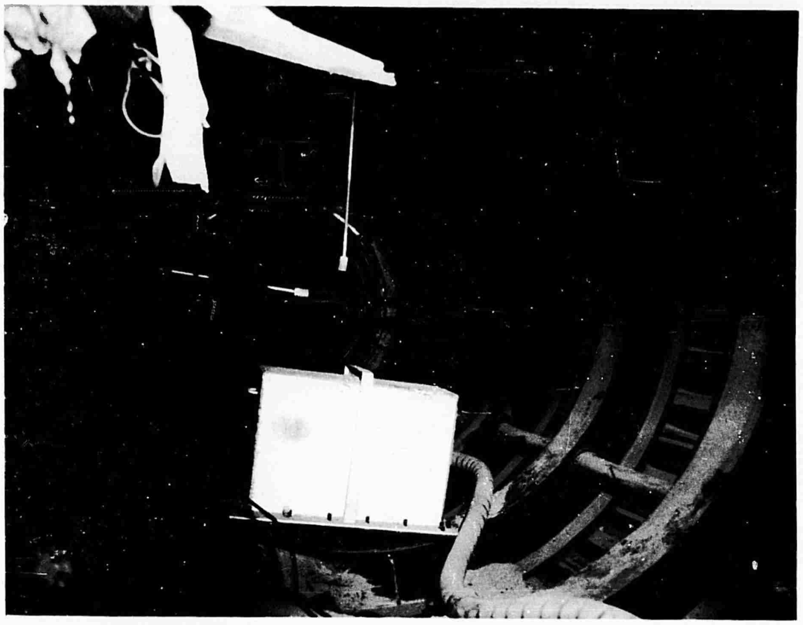

Figure 9 Covered radial gage in liner structure C4b, postshot. (FCWT DASA 281 (NOU-227-11) NTS-62)

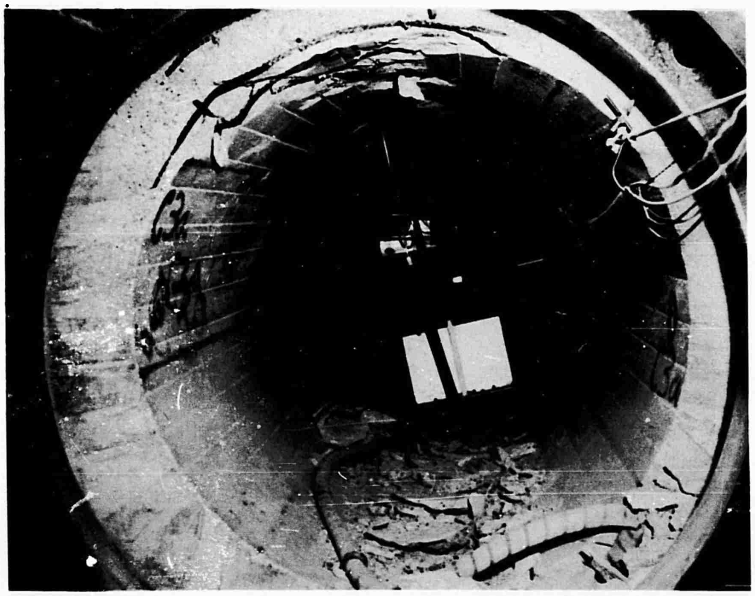

Figure 10 Covered radial gage in liner structure C3a, postshot. (FCWT DASA 281 (NOU-228-06) NTS-62)

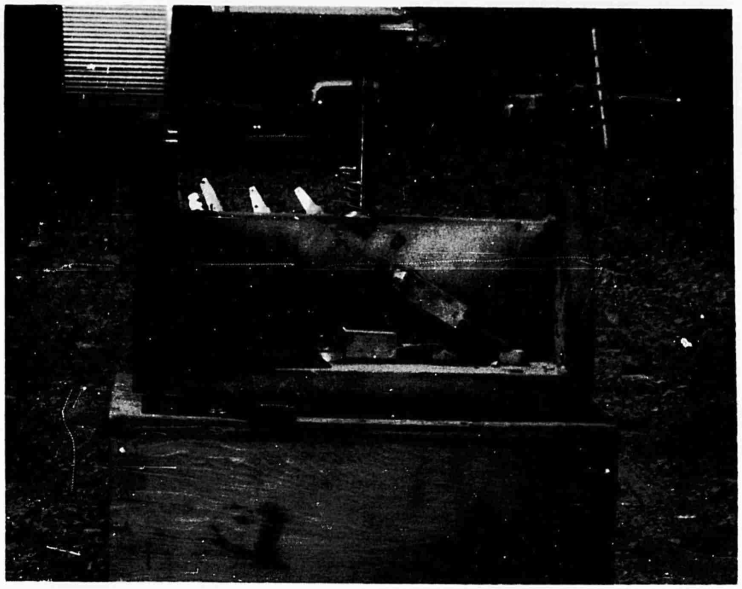

Figure 11 Damaged vertical gage from B drift access tunnel floor. (FCWT DASA 290 (238-01) NTS-62)

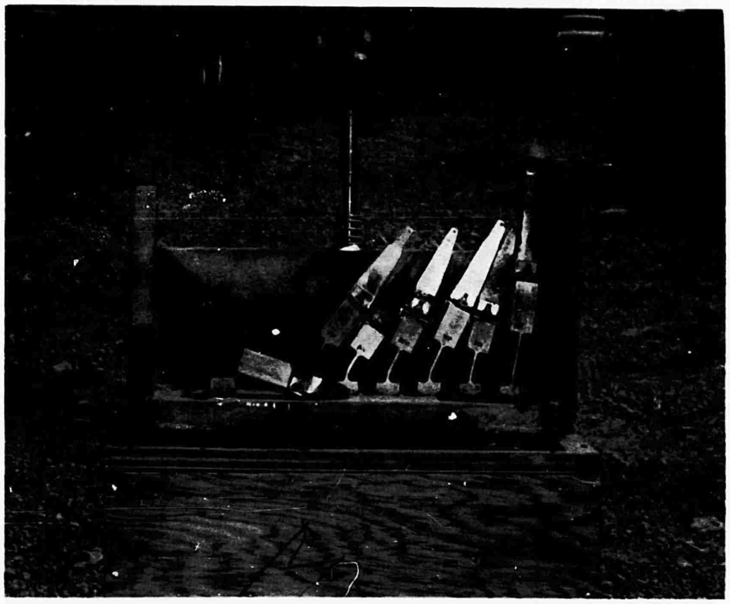

Figure 12 Additional view of damaged vertical gage from B drift access tunnel floor. (FCWT DASA 290 (NOU-238-02) NTS-62)

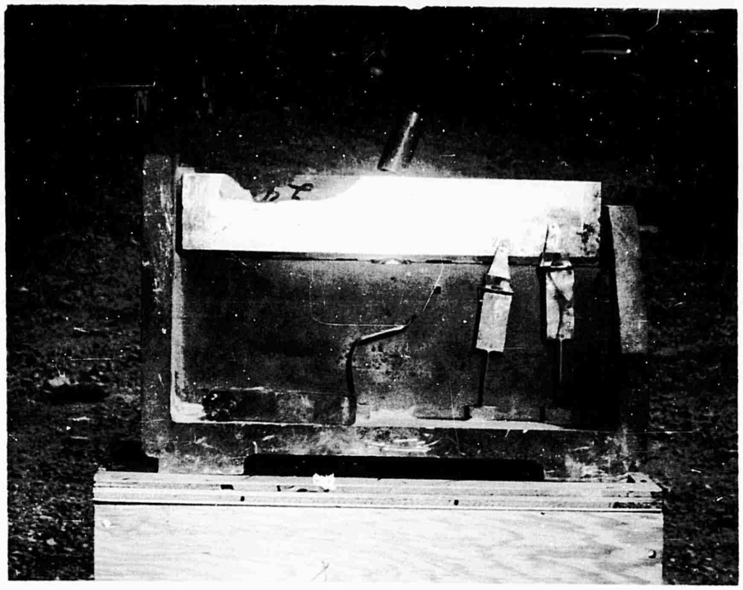

Figure 13 Damaged radial gage from B drift access tunnel floor. (FCWT DASA 290 (NOU-237-12) NTS-62)

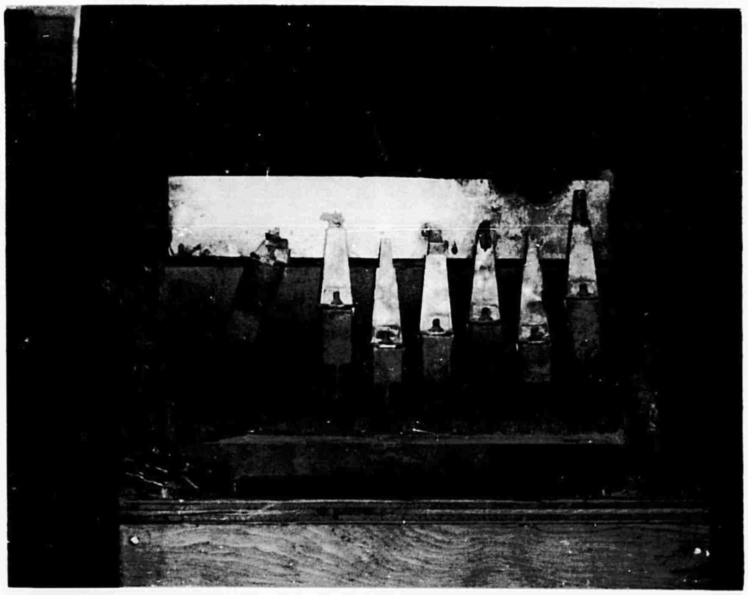

Figure 14 Additional view of damaged radial gage from B drift access tunnel floor. (FCWT DASA 290 (NOU-237-11) NTS-62)

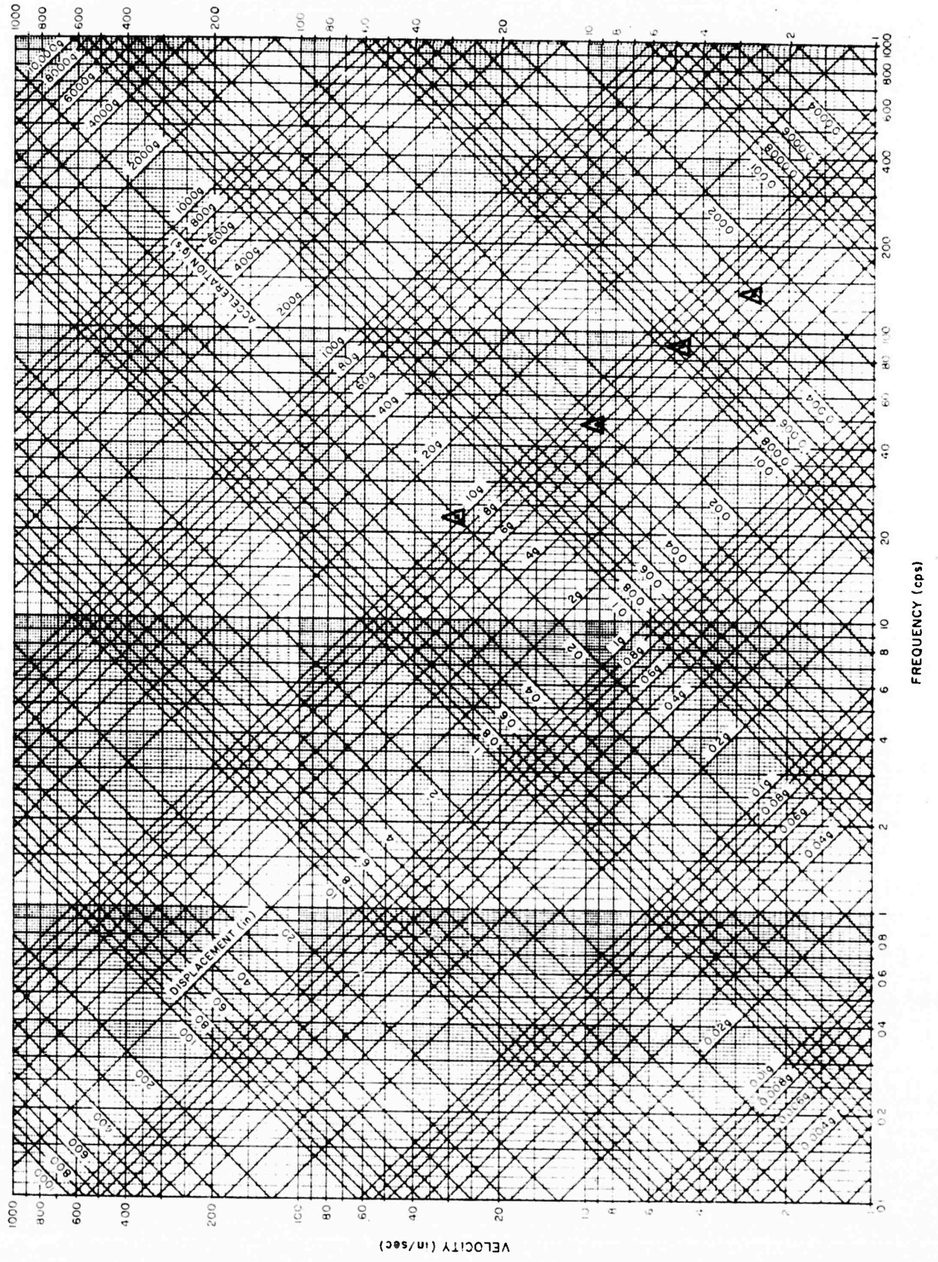

Figure 15 Vertical spectrum, Gage 1, surface, 1,340-foot radial distance to zero.

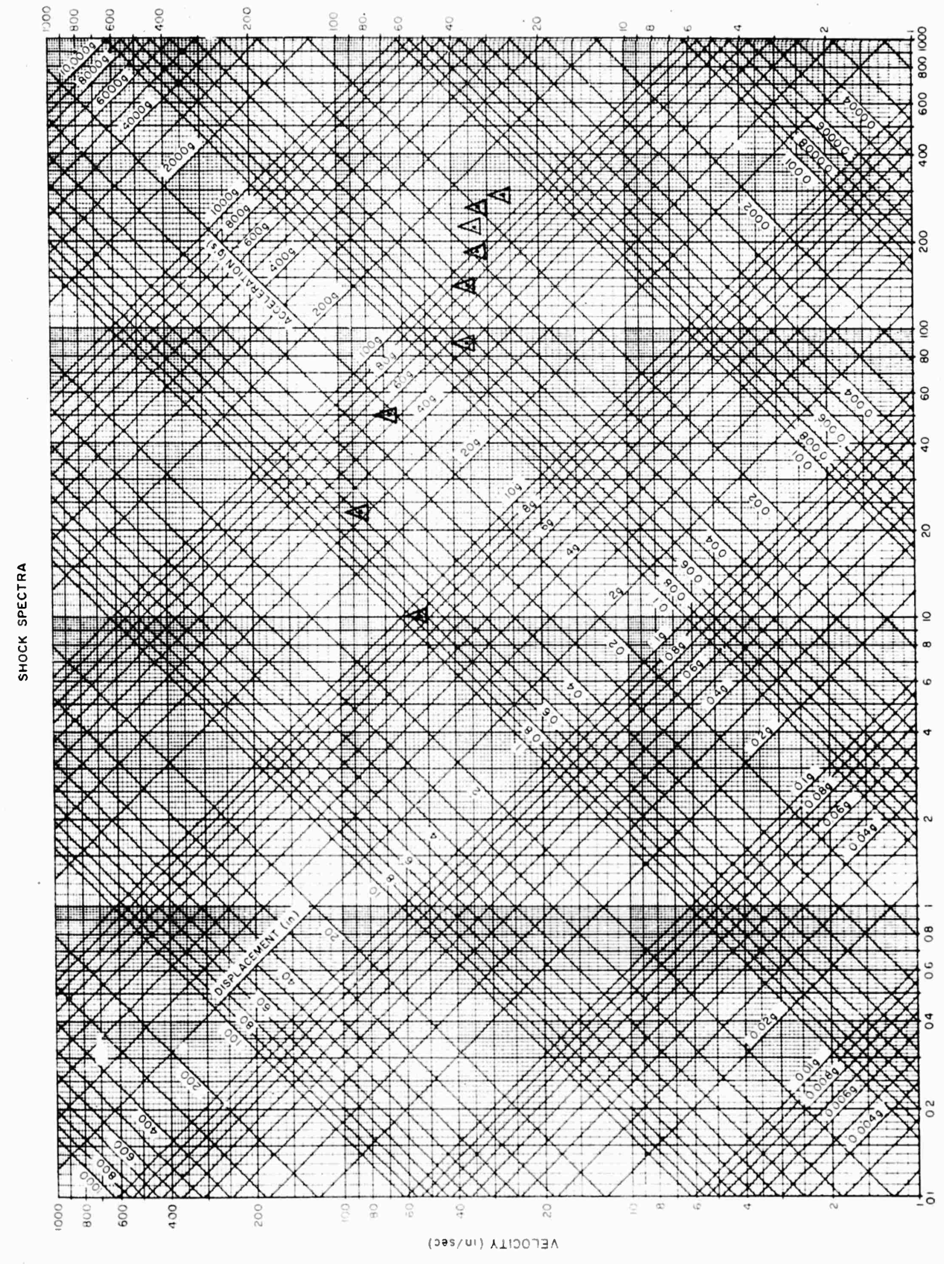

Figure 16 Vertical spectrum, Gage 16, access tunnel floor, 725-foot radial distance to zero.

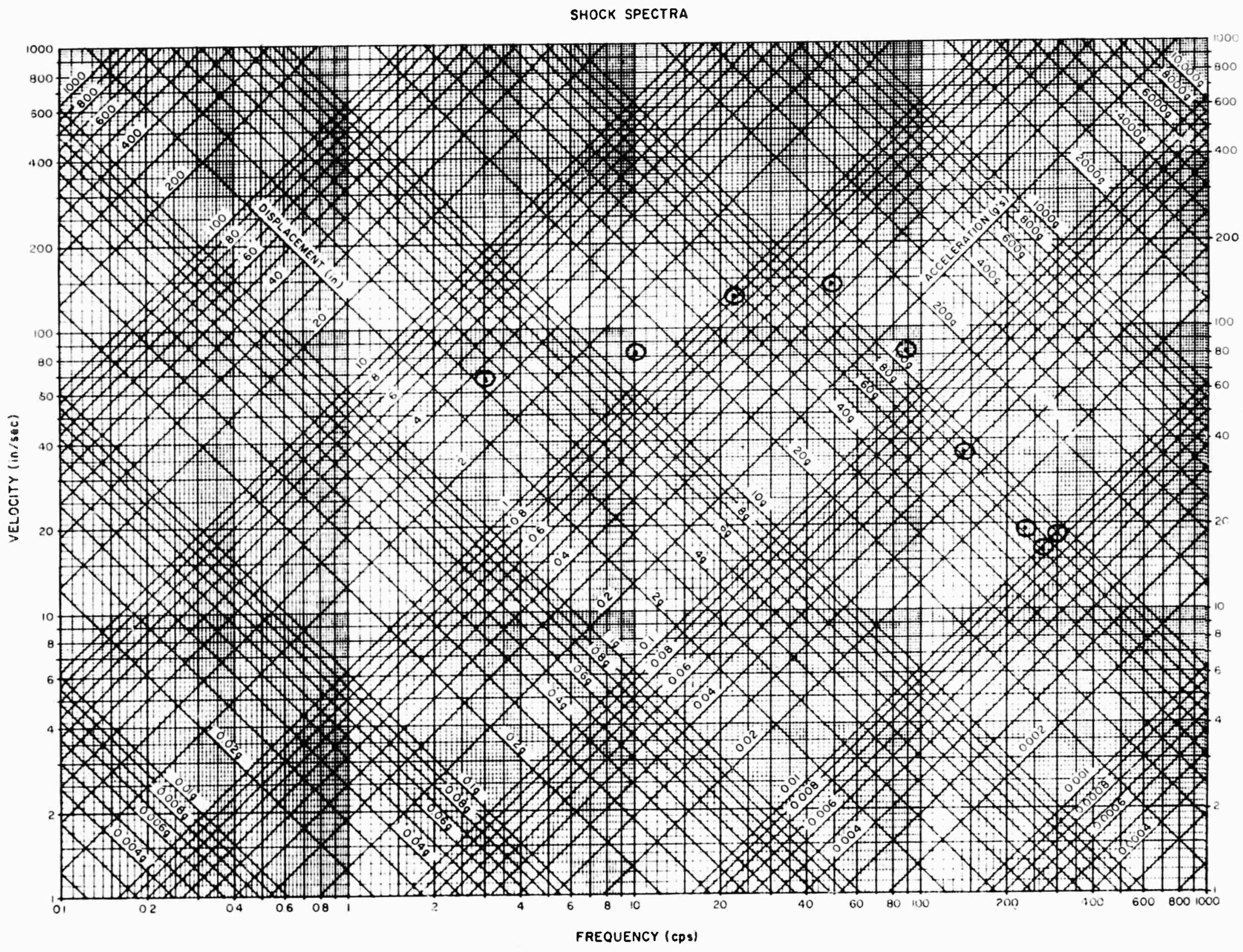

Figure 17 Radial spectrum, Gage 25, access tunnel floor, 725-foot radial distance to zero.

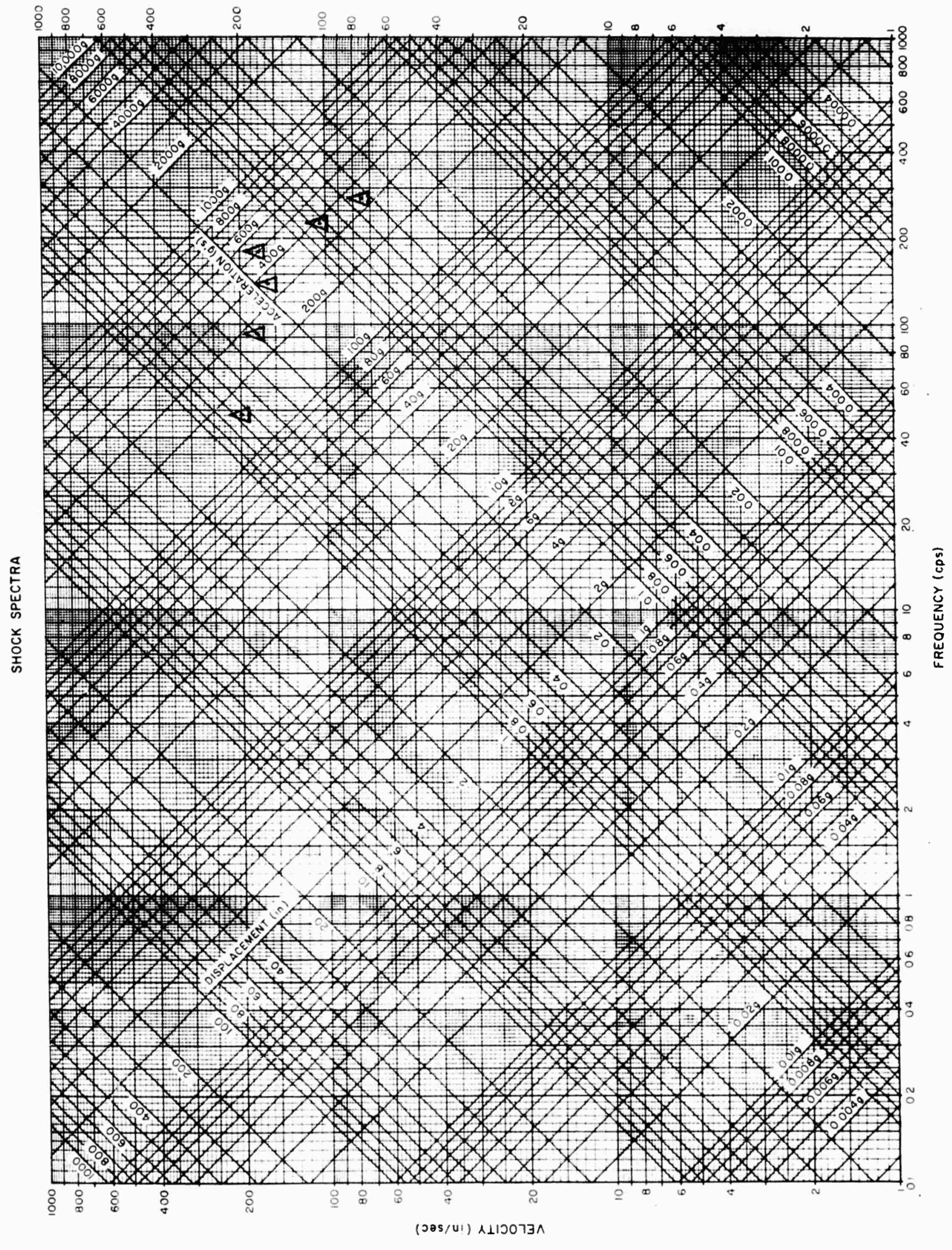

Figure 18 Vertical spectrum, Gage 26, C drift access tunnel floor, 460-foot radial distance to zero.

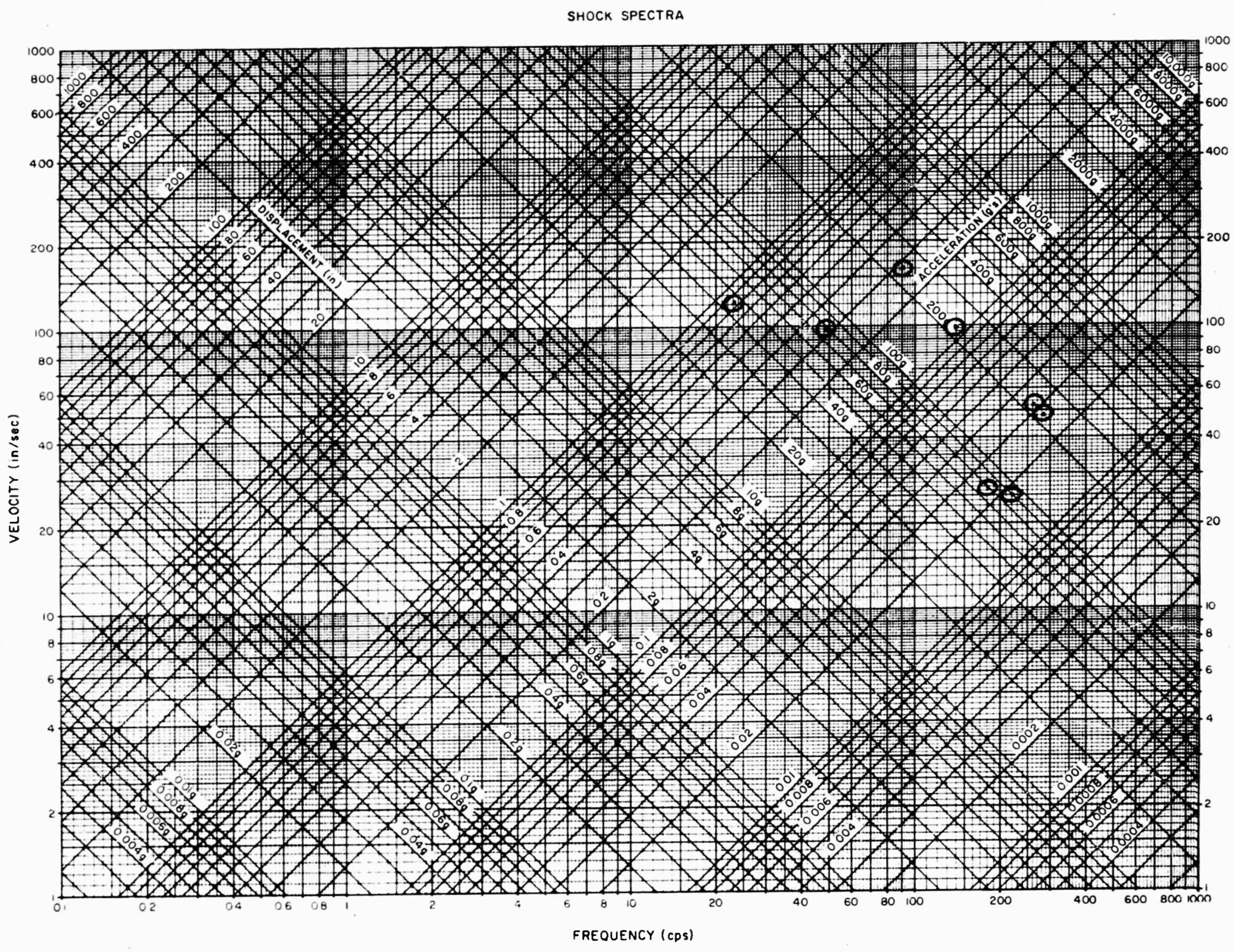

Figure 19 Radial spectrum, Gage 20, C drift access tunnel floor, 460-foot radial distance to zero.

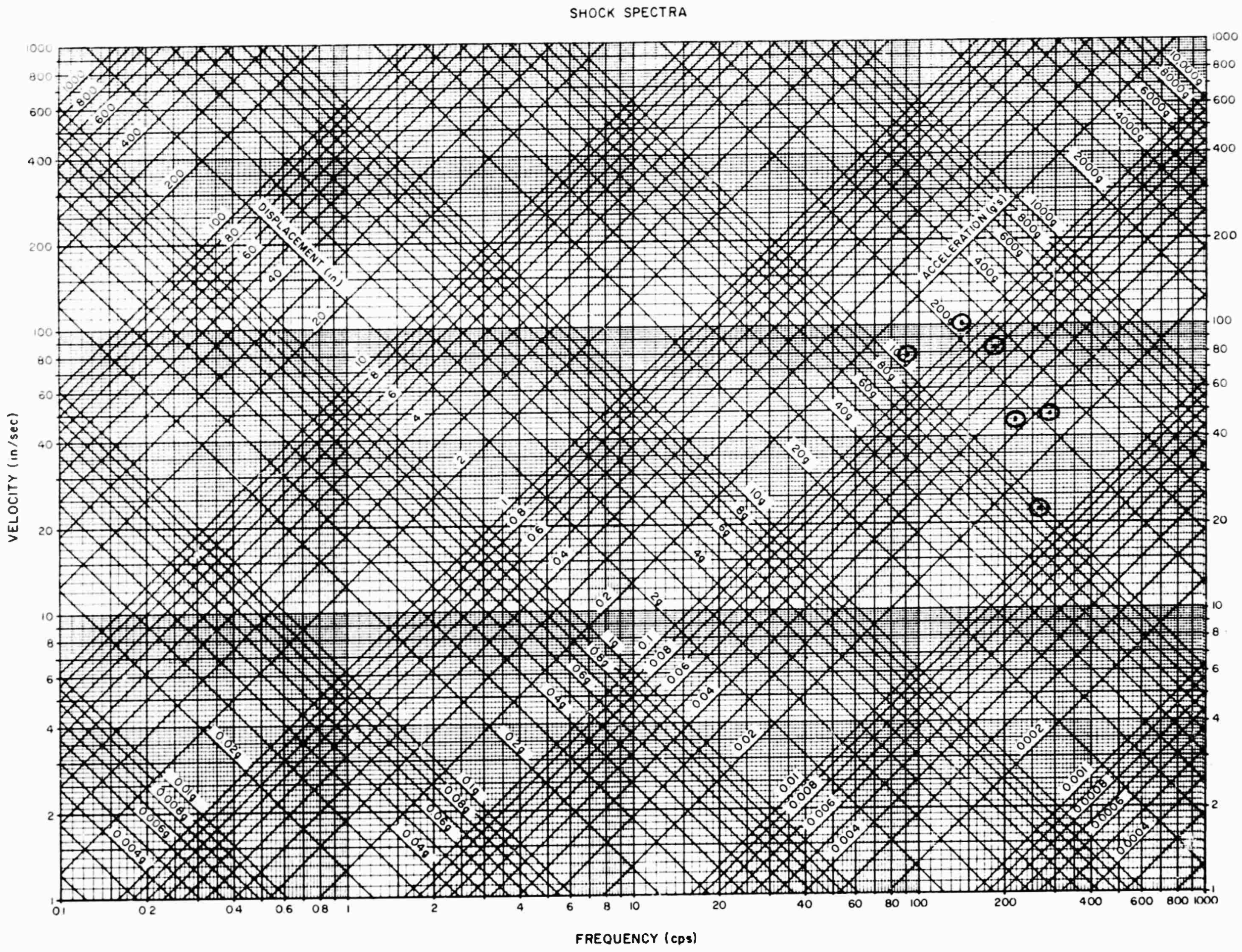

Figure 20 Radial spectrum, Gage 7, structure C3b (12-inch concrete, 5-inch foam), 460-foot radial distance to zero.

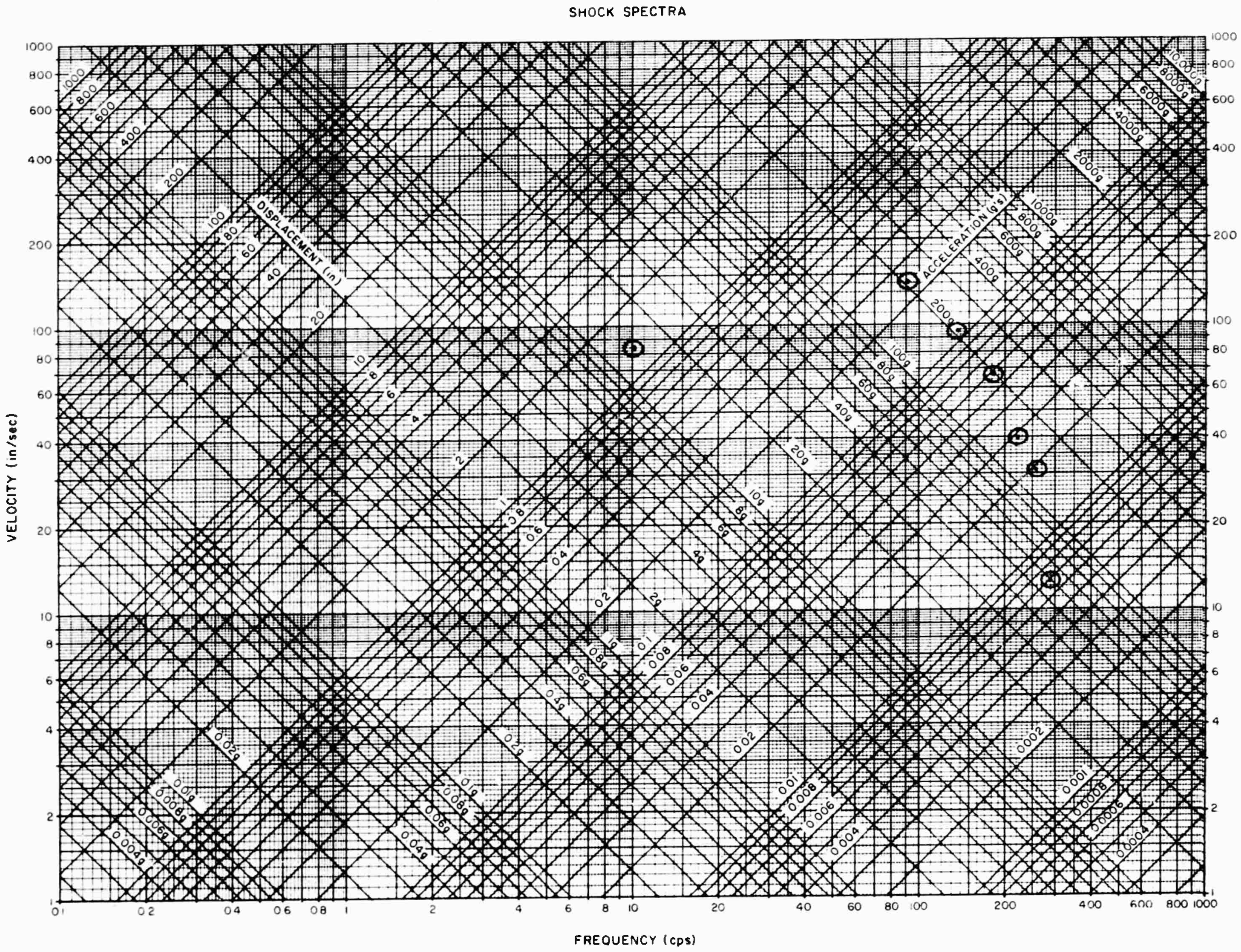

Figure 21 Radial spectrum, Gage 21, structure C3c (8-inch concrete, 24-inch foam), 460-foot radial distance to zero.

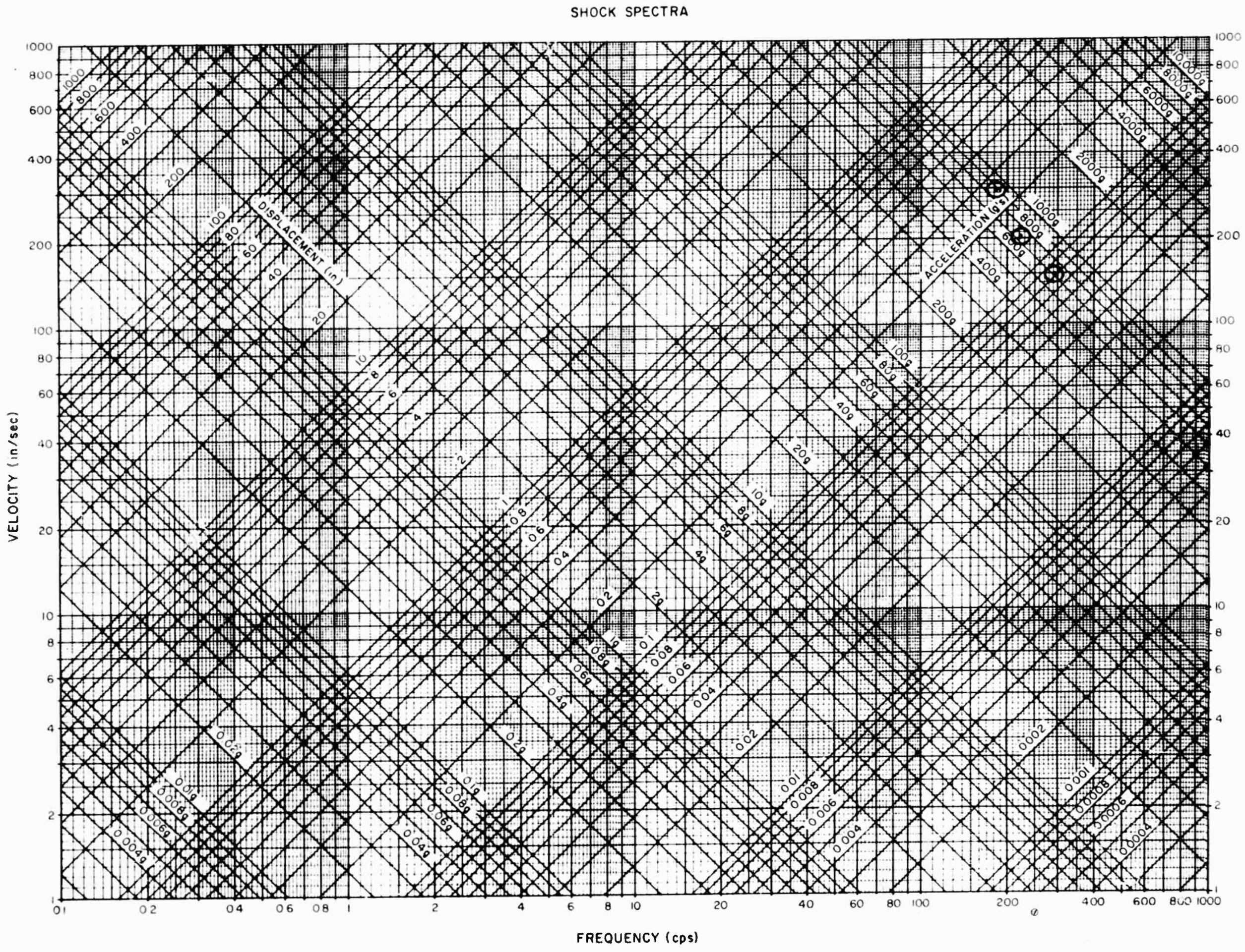

Figure 22 Radial spectrum, Gage 4, structure C3a (12-inch concrete against rock), 460-foot radial distance to zero.

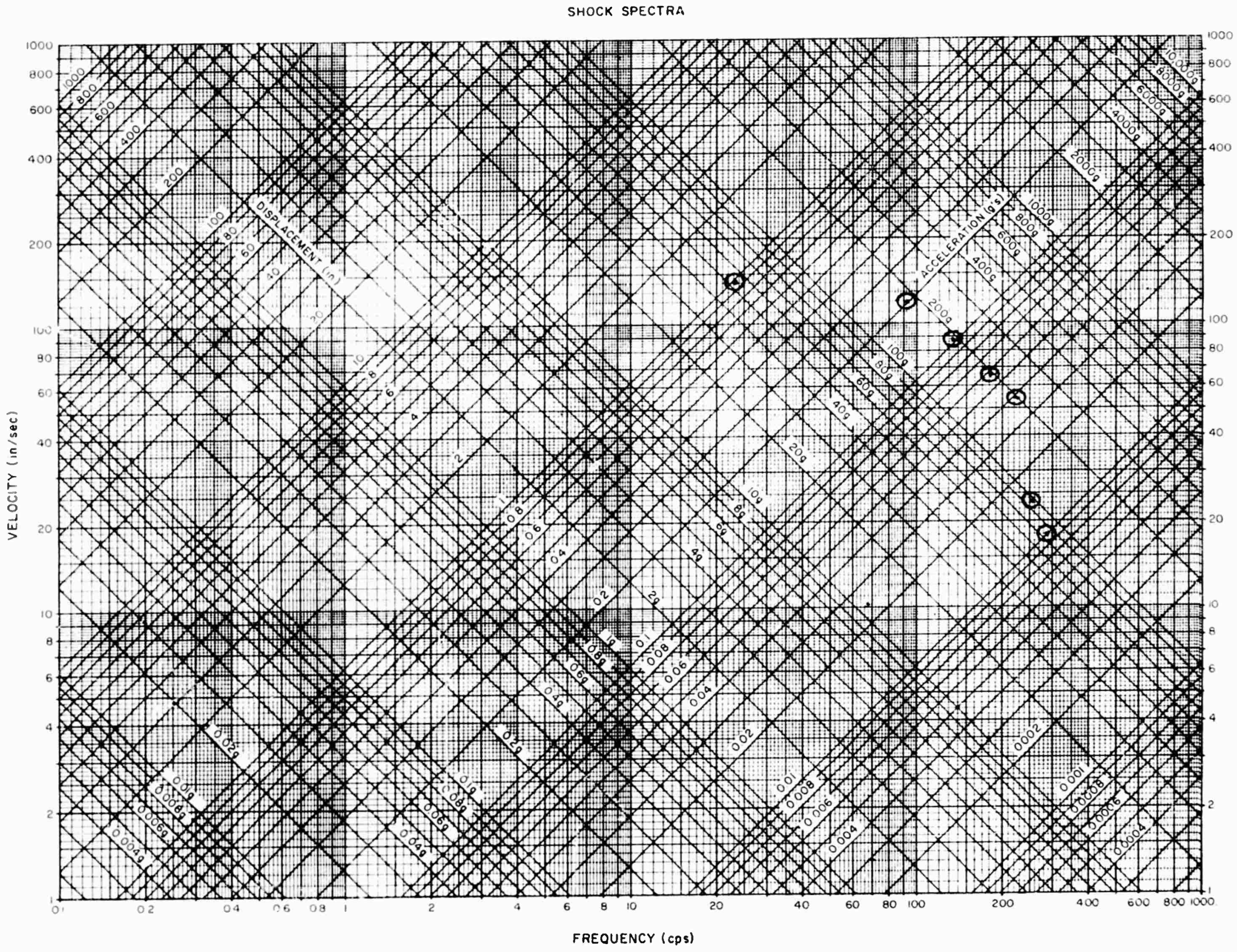

Figure 23 Radial spectrura, Gage 8, structure C4b (steel set, steel lag., 5-inch foam), 460-foot radial distance to zero.

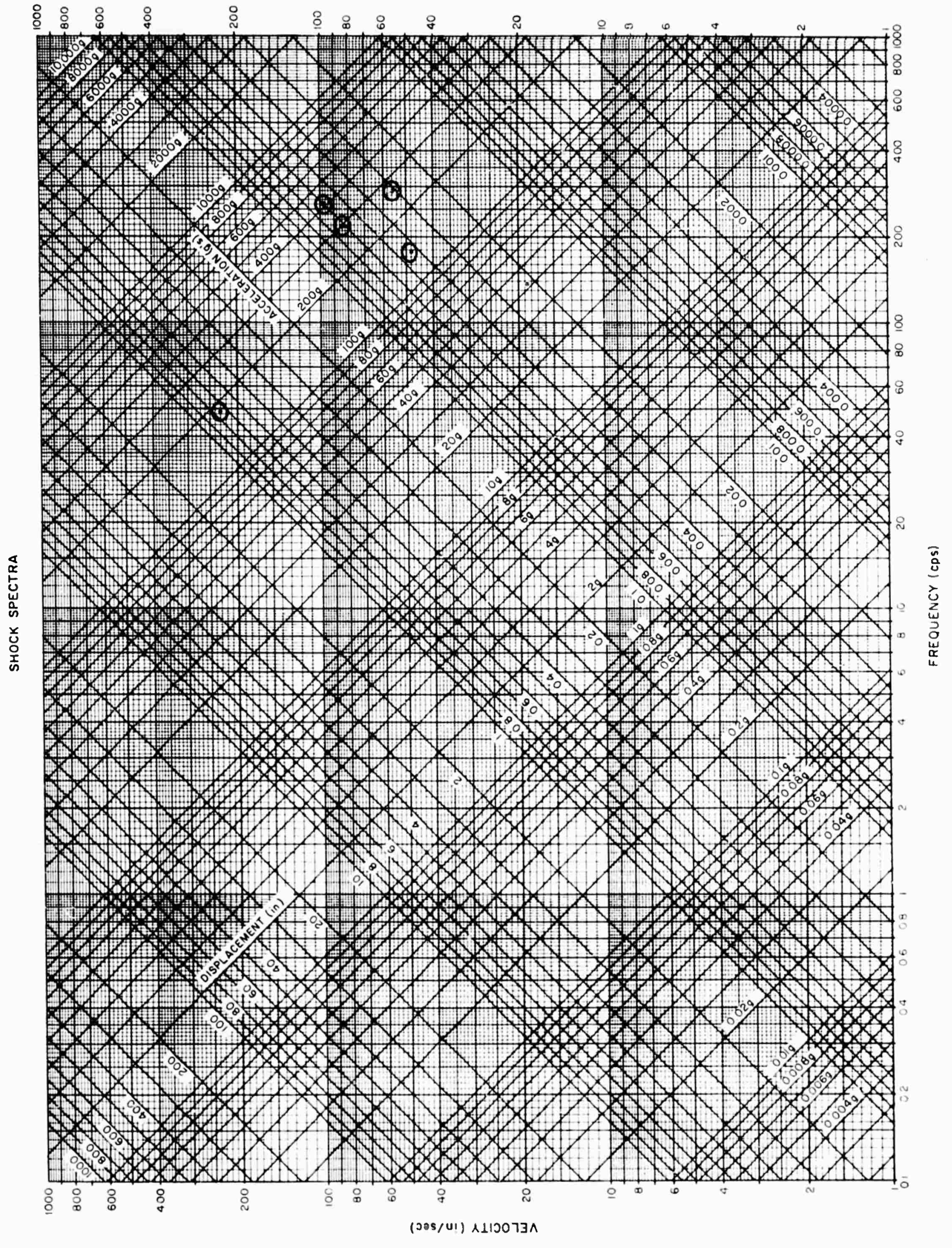

Figure 24 Radial spectrum, Gage 15, structure B3c (8-inch concrete, 24-inch foam), 340-foot radial distance to zero.

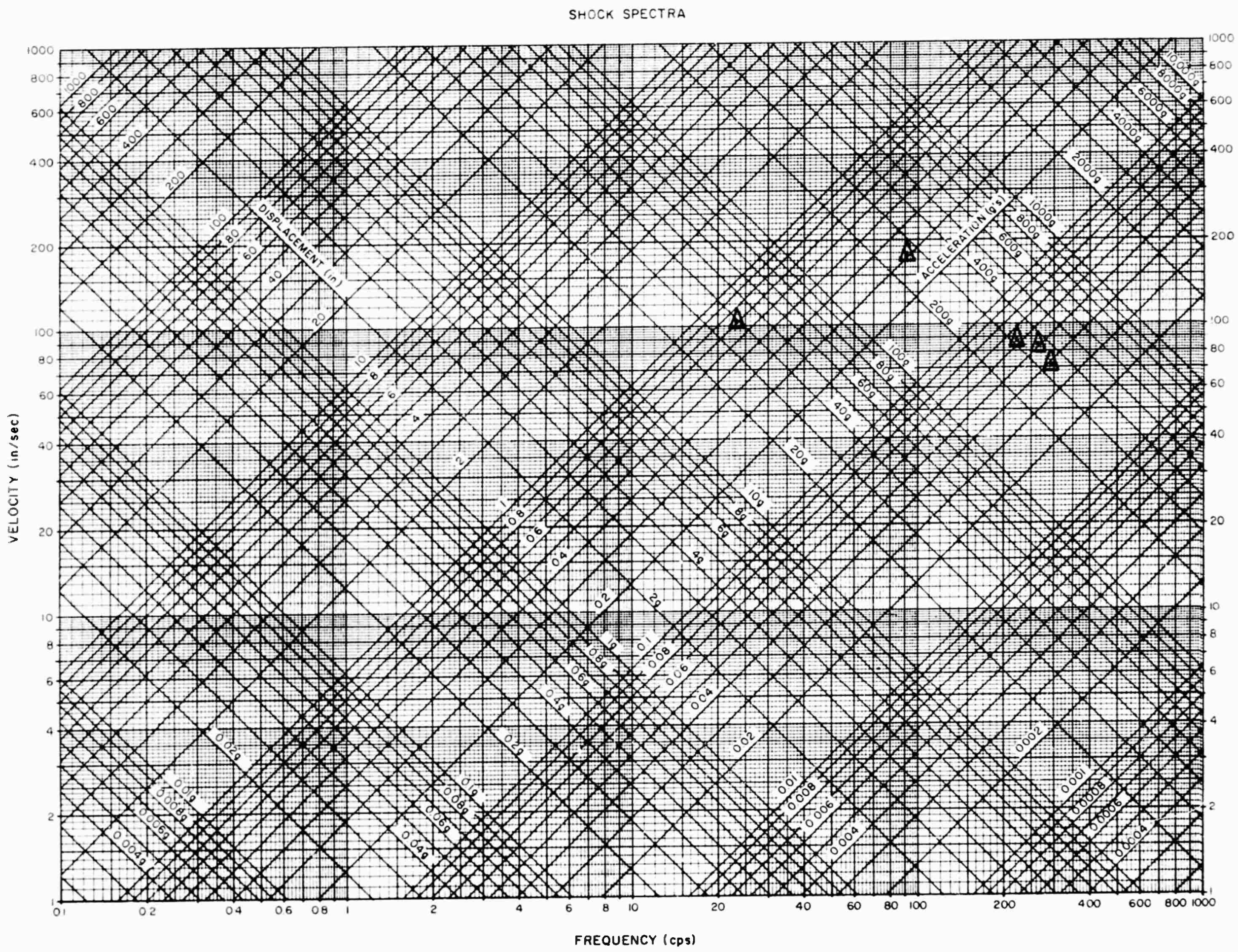

Figure 25 Vertical spectrum, Gage 5, structure B3b (12-inch concrete, 9-inch foam), 340-foot radial distance to zero.

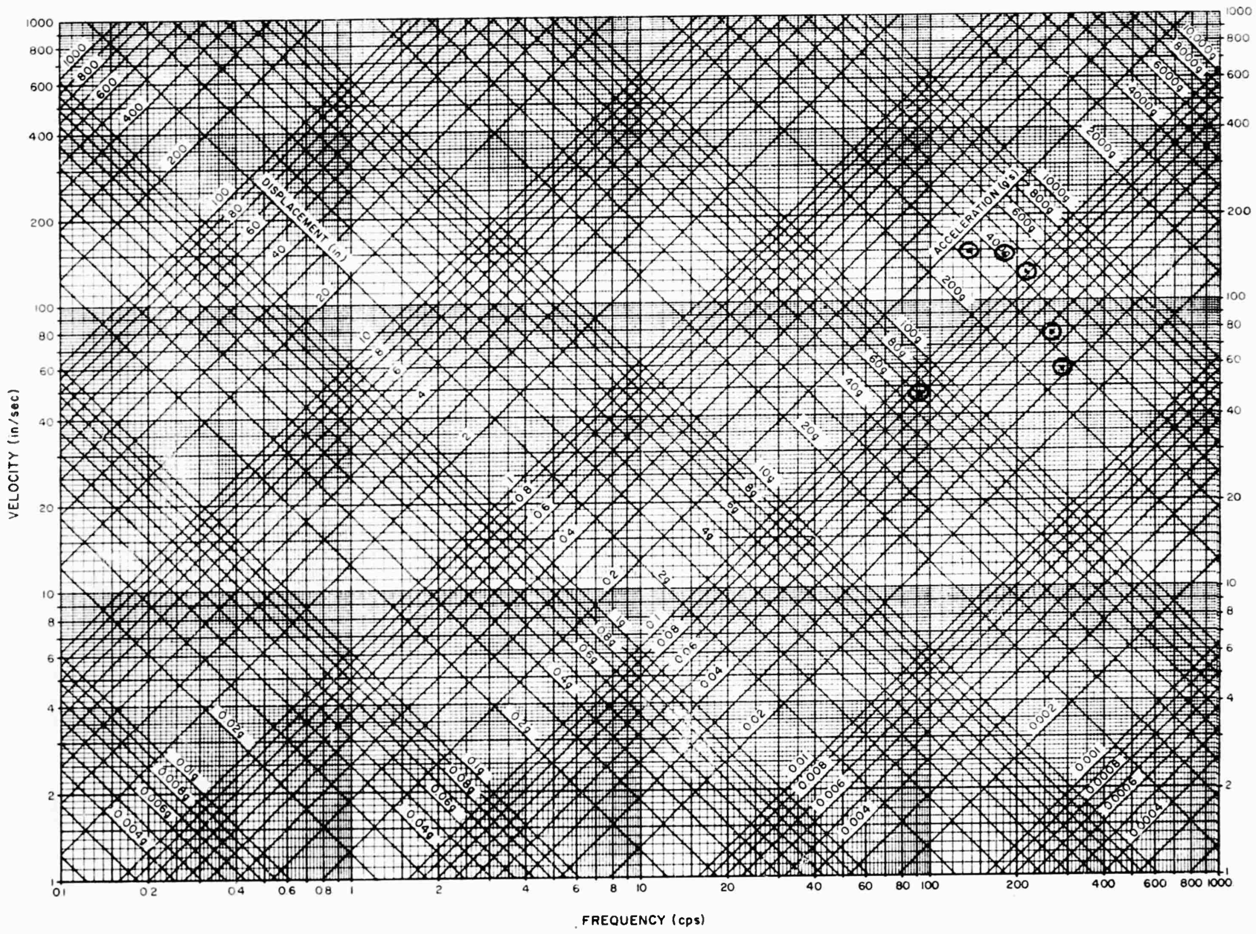

Figure 26 Radial spectrum, Gage 12, structure B3b (12-inch concrete, 9-inch foam), 340-foot radial distance to zero.

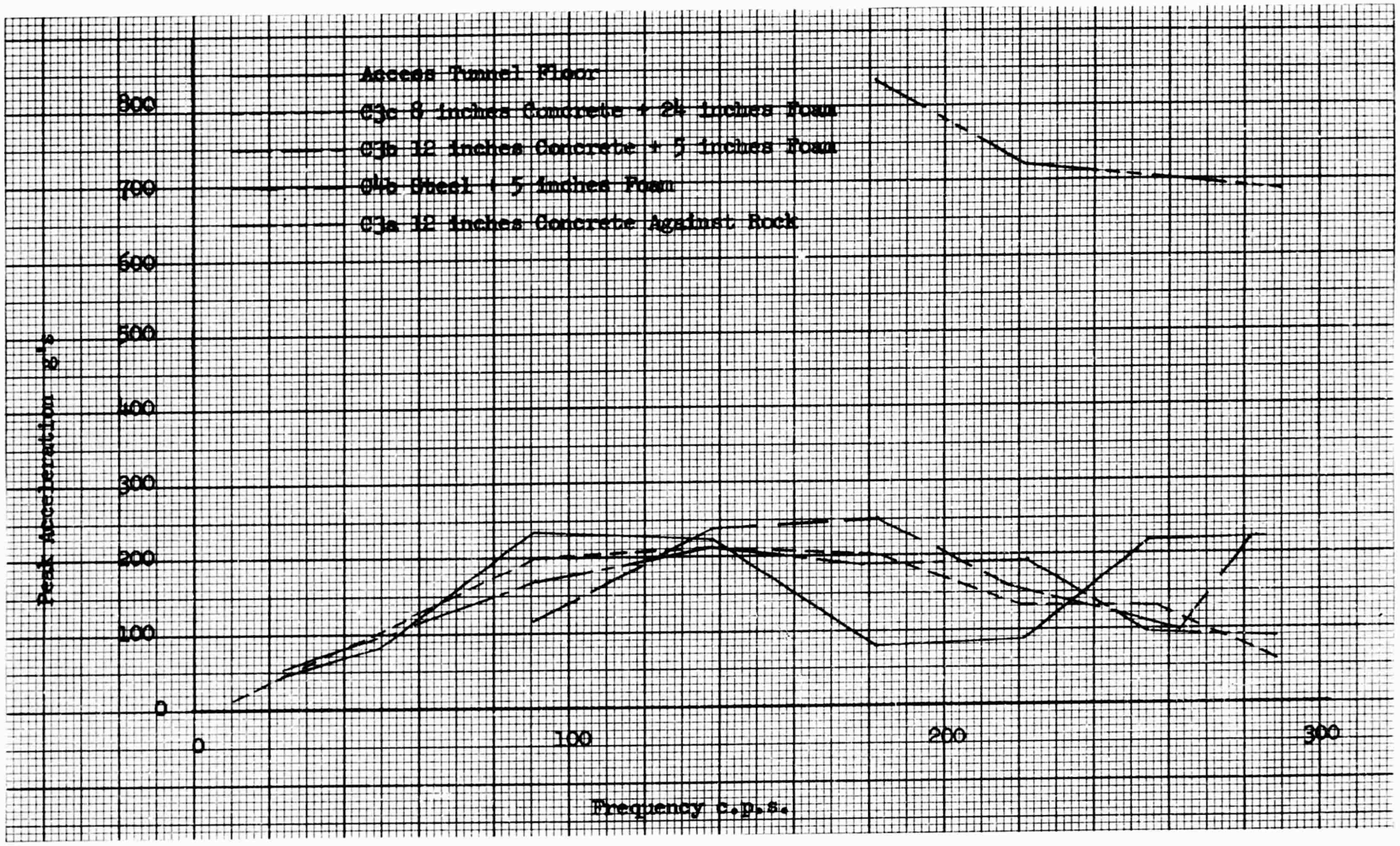

Figure 27 Peak radial accelerations C drift.

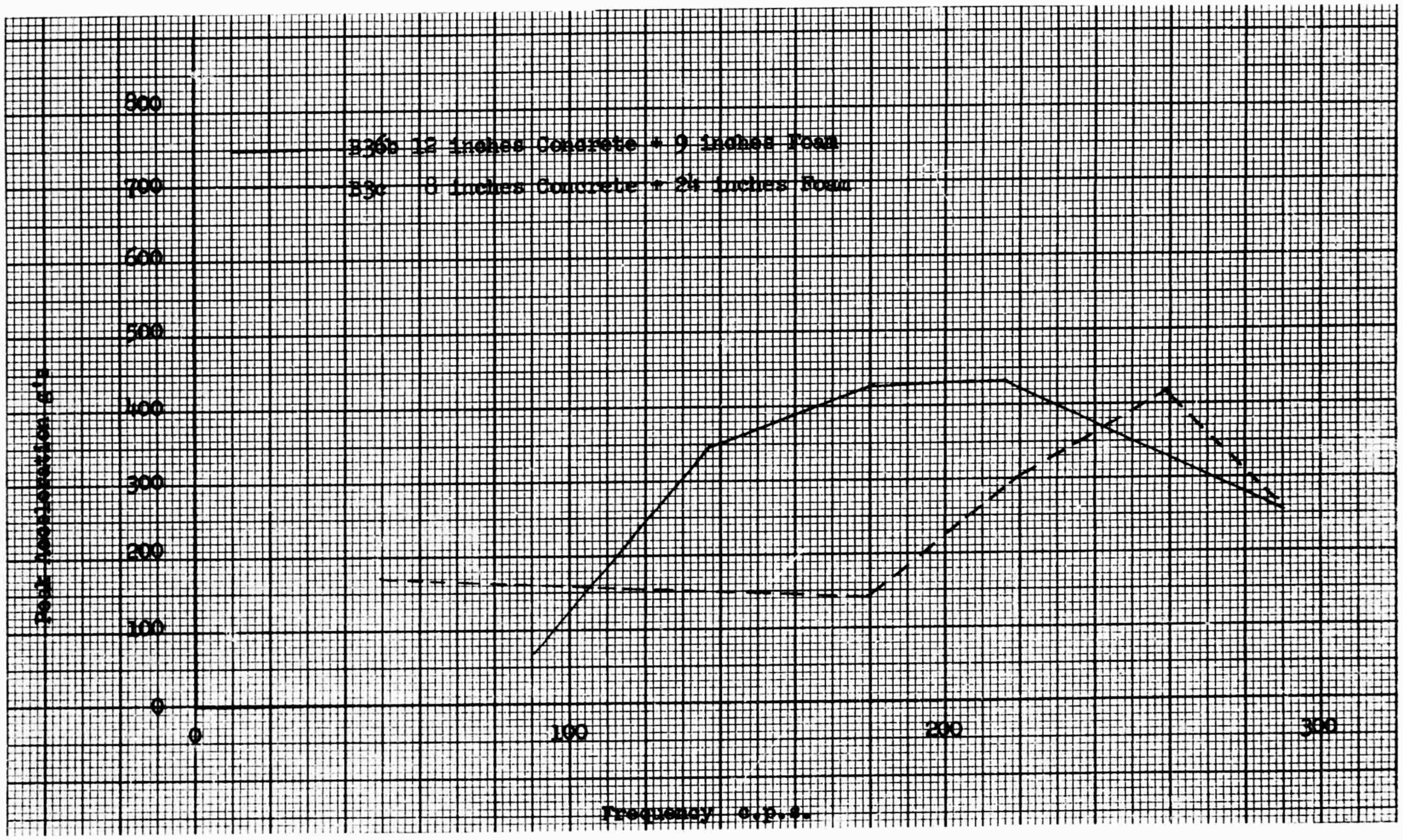

Figure 28 Peak radial accelerations B drift.

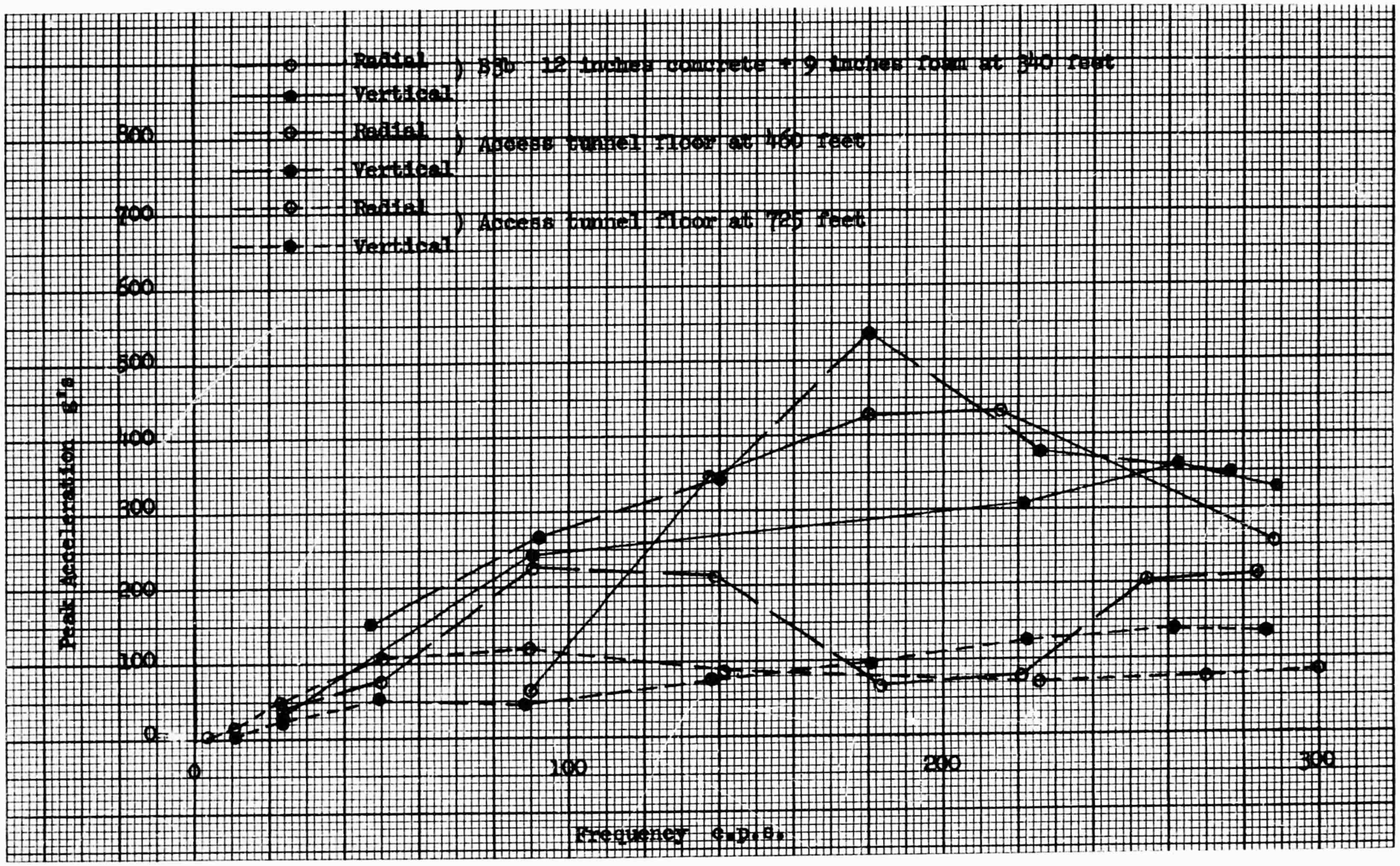

Figure 29 Comparison of peak radial and vertical accelerations.

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