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The 1969 Mono Lake experimental program was designed primarily to study the air blast from shallow underwater explosions of charges weighing five tons or more. This report documents the mapping of the underwater pressure field, which was done in support of the air blast effort. The underwater instrumentation was designed to measure secondary pressures due to bulk cavitation phenomena, as well as direct shock waves. The planning and experimental details are discussed, and the results given.

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UNDERWATER PRESSURE MEASUREMENTS AT MONO LAKE, CALIFORNIA - 1969

By
Joel B. Gaspin

30 SEPTEMBER 1970

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, SILVER SPRING, MARYLAND

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UNDERWATER PRESSURE MEASUREMENTS AT MONO LAKE, CALIFORNIA - 1969

This report is part of a continuing study of the interaction of underwater explosion shock waves with the water surface. The work described here was done in support of a study of the air blast from shallow explosions; however, knowledge of the sub-surface phenomena of nuclear explosions near an interface is important in itself for the evaluation of damaging effects on ships and submarines. The Mono Lake tests provided information concerning bulk cavitation and surface reflections that can be applied toward the improvement of existing prediction techniques for nuclear tactical situations.

This work was supported by the Defense Atomic Support Agency under Subtask NA002-22, Interface Influence on Underwater Explosion Effects, and Subtask NA007-06, Field Simulation Trials.

The author is greatly indebted to Robert S. Price for his guidance and suggestions during the preparation of this report. The experimental team directly concerned with the measurement of underwater pressures at Mono Lake consisted of R. S. Price, R. P. Altomare, J. B. Dempsey, J. B. Gaspin, R. L. Marbury, J. E. Morgan, W. R. Shaffer, P. A. Thomas, and R. B. Tussing.

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Captain, USN
Commander

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By direction

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1. INTRODUCTION

1.1 During the Summer of 1969, the Naval Ordnance Laboratory conducted an experimental program, involving the detonation of five large explosive charges under water, at Mono Lake, California. The primary objective of the program was the measurement of the air blast from large shallow bursts.[1*] A secondary objective was the measurement of the underwater shock waves and the bulk cavitation phenomena. This was done to evaluate the effect of the underwater pressures and the bulk cavitation on the air blast field, and to acquire knowledge useful for the prediction of the damaging effects of cavitation closure on ships and submarines. In order to achieve this objective, the Underwater Explosions Division undertook the mapping of the underwater pressure field. The measurements of the motion of the water-air interface were made under contract by the Engineering Physics Company[2] (EPCO). The present report documents the measurement of underwater pressures at Mono Lake, and includes a discussion of the implications of the results.

2. BACKGROUND

2.1 When a strong shock wave from an underwater explosion is incident upon the air-water interface, the reflected pulse tends to create sizable tensions in the water. Since water can only withstand weak tension,** the water will rupture or cavitate, producing an extensive region of water filled with bubbles of water vapor. This cavitation process begins some finite distance below the water surface, leaving a layer of uncavitated water overlying the cavitated region. The pressure in the cavitated region is very low, near the vapor pressure of water. The surface layer has been given an upward velocity by the passage of the direct shock and its surface reflection. Thus, the surface layer is spalled upward, and is accelerated downward by the force of gravity and the pressure difference across the spall.*** The spalled surface layer eventually falls back to its original position, impacting the by now quiescent water beneath, and causing secondary pressure pulses to be

---

* Refers to references on page 13.

** The degree of tension that sea water can withstand is not well known. It has been variously estimated as 600 psi by Kennard in reference 3, zero by Cushing in reference 6, and other values between these.

*** The interaction of the shock wave with the surface tends to produce spray at the surface. This effect is usually neglected in discussions of bulk cavitation.

emitted. The spall does not impact or close simultaneously at all horizontal ranges from surface zero. Closure occurs first at one horizontal range, and then progresses inward and outward from that location. The rupture process is generally termed bulk cavitation. Detailed descriptions of this process and associated phenomena are given by Cushing,[4,5,6] and Snay and Kriebel.[7]

2.2 The occurrence of bulk cavitation has been noted in connection with explosions of greatly varying sizes and geometries. The phenomena of spallation and closure affect the air blast field and generate sizable secondary pressure waves in the water. These secondary pulses may, under some circumstances, be of sufficient magnitude to cause damage to surface vessels and submarines. The cavitated region tends to greatly attenuate pressure waves passing through it, and could act to shield surface vessels from the bottom reflected shock wave. These considerations have motivated the study of bulk cavitation.

2.3 A theoretical treatment of bulk cavitation is given by Cushing.[4,5,6] This is an acoustic calculation which takes no account of the effect of the bottom, refraction, or anomalous cutoff. An experimental investigation to test this theory was made by Walker and Gordon.[8] In this experiment 10,000-lb HBX-1 charges were fired at 50 and 100-foot depths in 150 feet of water in the Chesapeake Bay. An unusual feature of these tests was the observation of negative bottom reflections. Since substantial tension waves were being reflected at both the water surface and bottom, two cavitation fronts were generated. These fronts tended to reinforce one another in some areas of the water, leading to greatly enhanced cavitation. Cushing's theory nevertheless yielded good agreement with measured surface motion and closure data. It appeared that the theory was adequate in these respects for the geometries tested. However, since all shots were at moderate depths, the theory had not been verified for relatively shallow shots. The Mono Lake program provided such a test.

3. THE TEST SITE

3.1 The program was carried out in Mono Lake, California. This is a large salt lake, situated at an altitude of 6400 feet, just east of the Sierra Nevada Mountains. The ambient atmospheric pressure at this altitude is about 11.5 psi.

3.2 Samples of lake water were obtained during the test (see below). Those from depths of 5, 40, and 75 feet below the surface were analyzed,* and the compositions are given in Table 1. The values are not greatly different from those on record at the Lee Vining Ranger Station. The composition of the lake water is much different from that of sea water. The percentage, by weight, of dissolved minerals is roughly twice that of normal sea water, and the specific gravity is approximately 1.05, as compared with a nominal value for sea water of 1.02.

TABLE 1

COMPOSITION OF MONO LAKE WATER

	5 ft Depth	40 ft Depth	75 ft Depth
Carbonate as Sodium Carbonate	11,000 mg/l.	13,000 mg/l.	12,000 mg/l.
Bicarbonate as Sodium Bicarbonate	3,400 mg/l.	5,400 mg/l.	6,000 mg/l.
Sulfate as SO_4	8,800 mg/l.	10,000 mg/l.	9,900 mg/l.
Calcium as Ca	17 mg/l.	91 mg/l.	25 mg/l.
Boron as B	84 mg/l.	132 mg/l.	127 mg/l.
Magnesium as Mg	30 mg/l.	51 mg/l.	26 mg/l.
Chloride as Chloride	8,000 mg/l.	9,000 mg/l.	9,000 mg/l.

3.3 It was noted that samples from increasing depths foamed or evolved gas (hydrogen sulfide was detected), and hence analysis of the samples is in error at least by the amount of gas lost. Furthermore, the effect of the dissolved gas on the sound velocity is unknown.

3.4 The tests were fired in 100 feet** of water, one-half mile out from shore. The structure and composition of the lake bottom is essentially unknown. One sounding during the test brought up a small quantity of material from the surface of the lake bottom. It was of a slimy consistency, organic in nature. The

* The analysis of water samples was done by C. W. England Laboratories, Inc., Washington, D. C.

** The nominal water depth was checked with a sounding during the program, and found to be correct within the accuracy of the sounding (~ ±2 feet).

quantity and distribution of such material on the lake bottom is unknown. On several occasions, immediately after a shot had been fired, large quantities of what appeared to be bottom material were seen floating on the surface. This indicates that at least the uppermost bottom layer was composed of matter not much more dense than the lake water.

3.5 A sound velocity profile for the lake was needed to determine the relative importance of refractive effects. Since no velocimeter was available at the test site, the following procedure was evolved. Samples of water from increasing depths were obtained in a small mouthed gallon jug by lowering it, weighted, stoppered, mouth up, and air-filled, to the desired depths. The stopper was then pulled with a small wire which reached the surface. After the jug filled with water it was pulled to the surface and the temperature of the sample measured with two household thermometers. The temperature profile obtained is shown in Figure 1. Parts of several samples of lake water were saved in storage jars for later analysis. After return to NOL, each sample was placed at the proper temperature for its depth and tested with a velocimeter. The velocity profile constructed in this way is shown in Figure 2. This profile was used in a ray tracing computer program at NOL. It was found that for the Mono Lake test geometries, refractive effects were entirely negligible. If a shot was fired in the lake at a greater depth of burst (e.g. 40 ft or greater), refraction might play a more important role.

3.6 Although there are no fish evident in the lake, the waters teem with brine shrimp (Artemia Salina). These creatures grow to a length of about 1/2 inch. No estimate of the concentration of these shrimp is available. It was noted, however, that in water samples obtained below a depth of about 20-30 feet, the concentration of shrimp was greatly reduced.

4. PLAN OF THE EXPERIMENT

4.1 The sizes and geometries of the shots at Mono Lake were determined solely upon consideration of the air blast study. The shot parameters are given in Table 2.

TABLE 2

MONO LAKE SHOT PARAMETERS

Shot	Explosive	Weight (lb)	Depth of Burst (ft)	Charge Radius (ft)
1	HBX-1	10,000	5.2	3
2	HBX-1	10,000	9.5	3
3	HBX-1	10,000	17.6	3
4	HBX-1	10,000	24.0	3
5	Lithanol	11,516*	10.7	3.5

* Actual weight determined at site.

4.2 The HBX-1 charges were cast spheres. The Lithanol charge was loose powder that was packed into a spherical steel case at the site.

4.3 For the various shot geometries, Engineering Physics Company provided predictions of the following: (1) spall closure time and depth vs horizontal range, (2) peak pressure and duration of secondary pressure pulse vs horizontal range. Using these predictions, the optimum horizontal ranges for the placement of four vertical gage strings were chosen. The closest station was situated outside the expected column radius, but as close as feasible to surface zero. The next station was at the range of maximum expected secondary pressure levels. The third station was at the predicted horizontal range of first closure. The outboard station was near the range of longest predicted duration of the secondary pressures. The array of gage station locations is given in Table 3.

TABLE 3

HORIZONTAL RANGE TO GAGE STATIONS (FT)

Shot	Station Number 1	2	3	4
1	150	215	275	350
2	150	255	320	400
3	175	290	380	500
4	175	290	380	500
5	170	235	295	400

4.4 At each gage station, a string of tourmaline piezoelectric gages was suspended. The gage depths at each station were 2, 11, 22, 33, 44, 50, 55, 66, 77, 80, and 88 ft. It was felt that with this array, the following information could be obtained:

4.4.1 Extent of the cavitated region. At a given point in the water, if cavitation occurs, the arrival of the surface reflection of the shock wave should lower the ambient pressure from the hydrostatic head to the vapor pressure of water. The pressure stays roughly constant at this level until closure occurs. This apparent baseline shift of the gage record is a clear indication of the occurrence of cavitation.*

4.4.2 The closure process. When the cavitated region closes, secondary pressure pulses are emitted. The placement of the gage array should allow the time and depth of closure and the secondary pressure and duration to be determined at several crucial horizontal ranges.

* R. A. Wentzell, et al, in reference 9, suggest the appearance of a sharp negative pressure pulse as an indication of cavitation. The frequency response of the recording system at Mono Lake would not allow such a spike to be detected.

4.4.3 Mapping of the shock pressure field. It is well known, that for most shallow underwater explosions, a region exists in which the surface reflection, traveling in a shocked medium, has caught up with the direct shock, and arrives coincident with it, eroding the peak pressure, and changing the wave shape. This is known as the region of anomalous surface cutoff. The boundary of this region may be calculated using the method of Keil,[10] and is shown in Figure 3 for each shot. As the depth of burst is decreased for a given charge weight, the anomalous region comes closer to the burst point, and encroaches more into the region of interest at Mono Lake. In this region, the entire picture of a shock arrival followed by a surface reflection must be abandoned. The normal similitude equations break down, and the pressures and pulse shapes must be calculated using a non-linear approach. This has been done by Rosenbaum and Snay.[11] Since Cushing's theory is linear, and assumes the particle dynamics of a standard oblique reflection, one would not expect the calculation to hold in the anomalous region. However, since no non-linear cavitation calculation has been done, the linear theory was used to determine test geometry.

5. INSTRUMENTATION

5.1 Four instrumentation stations were utilized on each shot in the program, one at each of the ranges indicated in Table 3. Each station consisted of a wooden platform, approximately 12' x 12', supported by empty oil drums lashed to the underside. Each platform was open at the center to allow for the mooring of the EPCO volocity meters. A string of gages was suspended from each platform. These gages were tourmaline piezoelectric (PE) gages made by Crystal Research Corporation. The waterproofing configuration for these gages is shown in Figure 4. Each gage was mounted on leads molded into an epoxy oil barrier. The leads were attached to a coaxial cable, and the connection waterproofed with Bostic 2292 and rubber tape. The gage was sealed into a plastic tube filled with 100-centistoke silicone oil (Dow Corning DC-200). Research conducted at NOL had indicated that this method of waterproofing affects the gage output less than any of the several other methods tried. The output of each gage was conditioned and calibrated by a gage signal amplifier (GSA), and recorded on tape recorders that had been developed with DASA funding under DISTANT WATERS Project LN-501. The GSA's and the recorder for most gage strings were located on the instrumentation platform above the string. The GSA's and recorder for the innermost station were mounted on the second platform.

5.2 Each gage string consisted of eleven PE gages, suspended at the depths previously given in paragraph 4.4. The instrumentation rig is shown in Figure 5.

5.3 A Model 911 time code generator made by the Electronic Engineering Company was used to provide a time code to all recorders (underwater, airblast, and surface velocity). This provided a common time base for all records as well as positive shot identification by dating. This time code has a 10-kHz carrier frequency.

5.4 In order to better resolve the expected secondary pressures, at a given delay after the shock arrival, a padding capacitor in the gage input circuit was disconnected to increase the gain on each recorder channel. The gain was generally increased by a factor of 10 to 20, as predetermined for each channel.

6. ANALYSIS METHODS

6.1 The underwater pressure data consists of pressure time records on magnetic tape. All tapes were played back on the DISTANT WATERS tape playback system, an in-house developed unit, as are the portable recorders. Analysis of this data was performed in two ways:

6.1.1 Analogue analysis. Visicorder playouts of all the records were made. From these playouts, the important arrivals could be located and arrival times read from the time code present on each tape.

6.1.2 Digital analysis. Each of the records was digitized and analyzed on the IBM 7090 computer using a computer program developed by R. S. Price of NOL. This program corrects the nonlinearity of the recording system used at Mono Lake, and provides a readout (in psi) of the direct shock pulse.

7. RESULTS

7.1 At Mono Lake, 152 valid pressure time histories were obtained from a total of 220 data channels (5 shots, 4 recorders per shot, 11 data channels per recorder). Of these 152 records, 105 could be utilized throughout the entire record. A typical set of records from a single gage string is reproduced in Figure 6.

7.2 The noise level on most channels was generally high. At the present time, the cause of this noise has not been determined.

7.3 Neither of the anticipated indications of cavitation phenomena, the drop below ambient pressure, nor the appearance of secondary pressure pulses, was

evident in the pressure-time histories. However, there is other evidence that bulk cavitation did occur. The surface velocity histories of reference (2) indicate that cavitation occurred. If cavitation does not occur, the water remains a continuous medium. This results in a time of flight (from shock wave arrival to restoration of the original surface position) considerably shorter than those indicated by EPCO's surface motion data.* This is an indication that cavitation did occur at Mono Lake.

7.4 That the theoretically predicted characteristics of the cavitation phenomena were not observed is not surprising. As pointed out above, in paragraph 4.4.3, Cushing's calculation makes assumptions that are clearly not valid for the Mono Lake test geometries. Consequently, the gages were not placed in the proper locations to observe cavitation phenomena.

7.5 Besides the direct shock arrival, there was, in general, at least one bottom reflected pulse on most of the records. In some cases, two bottom reflected arrivals were noted. The bottom reflections were always positive, indicating that the bottom was of greater acoustic impedance than the water.

7.6 To provide correlation with the air blast and surface motion data, the surface arrival times of the direct and bottom reflected primary pulse were determined from the data and are given in Tables 4 and 5. These arrival times are precise to ±0.1 msec. They agree with those given by Schultz and Cushing[2] if the ±.5 msec precision of those data is considered.

TABLE 4

SURFACE ARRIVAL TIME OF DIRECT SHOCK** (msec)

	Station Number			
Shot	1	2	3	4
1	27.2	39.7	52.1	65.8
2	27.7	--	60.1	76.1
3	32.4	54.2	71.7	94.8
4	--	54.1	72.6	95.7
5	27.6	44.2	54.9	75.9

*The dynamics of the surface, with and without cavitation, is discussed by Malme, et al, in reference 12. See particularly pp 48-52.

**All times are measured from the time of detonation.

TABLE 5

SURFACE ARRIVAL TIMES OF BOTTOM REFLECTED SHOCK (msec)

	Station Number			
Shot	1	2	3	4
1	50.6	58.0	68.0 72.8	--
2	--	--	78.7	86.5
3	--	73.1	86.3	103.9 107.5
4	--	73.6	87.6 93.0	109.4
5	--	--	69.8 74.7	--

Where two times are given, two distinct arrivals were noted.

7.7 Some of these arrival times are considerably later than calculated from nominal shot geometries. Schultz and Cushing concluded that this indicated that cavitation was present in the water, since Cushing[3] showed that sound speed in cavitated water is very slow. To check this conclusion, plots were made of the arrival times of all important pulses for each gage string (Figures 7 through 17). Extrapolating the direct and bottom reflected arrivals, the depth of the bottom reflection was determined. The bottom reflection, in general, occurred at a greater depth than the nominal bottom depth. This factor alone accounts for the delayed arrival times reported by Schultz and Cushing, and indicates that their conclusion was incorrect. It is clear that in some cases two distinct reflections, originating at distinct depths, occurred. This is indicative of the bottom stratification.

7.8 The peak pressures for the direct shock were determined, and compared with theoretical predictions (Figures 18 through 31). These figures give experimental and theoretical peak pressures for a vertical gage string. The theoretical pressures were calculated by the method of Rosenbaum and Snay,[11] using a computer code developed by J. R. Britt of NOL. The theoretical curves show low pressures at the surface, due to erosion of the peak by anomalous cutoff, a gradual increase

with depth, as the pulses become less anomalous, and then a decrease in pressure with depth below the anomalous region. The general character of the measured pressures is most clearly seen in the data from Shot 1 Station 1 (Figure 18). The variation of peak pressure with depth is radically different from that which theory predicts. A possible explanation for these results is given below.

7.9 As mentioned above, there is a great concentration of brine shrimp in the Mono Lake water. Gruber and Meister[13] showed experimentally that suspensions of brine shrimp cause excess attenuation of sound waves in water. At Mono Lake, the upper 30 feet of water is particularly thick with the brine shrimp. The concentration falls off below that depth, corresponding to a sharp decrease in water temperature (see Figure 1). It is not known how the concentration of shrimp varies in the upper 30 feet. If the concentration of shrimp is greatest at some depth between the surface and 30 feet, the variation of pressure with depth may be qualitatively explained. Rays which travel from the source to shallow gages travel through varying concentrations of shrimp and are greatly attenuated. As deeper gages are considered, the rays travel shorter distances through the regions of high shrimp concentration, and are less attenuated. Thus it appears that the peak pressures may reflect the brine shrimp concentration and are not indicative of what would occur in an ocean environment.

8. CONCLUSIONS

8.1 The bulk cavitation theory of Cushing is not adequate for the Mono Lake test configurations. Since it doesn't consider the anomalous cutoff effect (see paragraph 4.4.3), it is inadequate for relatively shallow shots, that is, shots for which the boundary of the anomalous region encroaches into the region of interest. For 5-ton HBX-1 charges, Cushing's theory suffices for burst depths of approximately 40 feet and greater. For other charge weights and compositions, individual computations must be made, since bulk cavitation and anomalous cutoff cannot be scaled simultaneously.

8.2 Further, the failure of theory to consider the effect of the bottom reflected shock wave restricts its applicability to geometries such that the bottom reflected pulse arrives in the region of interest only after cavitation closure has occurred.

8.3 There are no indications of cavitation phenomena in the underwater pressure data. This is probably because the gage positions were based on incorrect predictions.

The surface velocity histories of reference (2) indicate that cavitation did occur (see paragraph 7.3), but it seems likely that the events of interest were not of sufficient magnitude to be recorded at the gages.

8.4 The pressure field data show a unique character which is not predicted by theory. This may be explainable with reference to the large concentration of brine shrimp in the water at Mono Lake. These shrimp have been shown, experimentally, to cause excess attenuation of sound waves in water.

8.5 The body of underwater data obtained in this program is of use mainly in correlation with the surface motion and air blast data obtained in the same program. The unusual character of the data seems a function more of the peculiar characteristics of the test site than of the explosion phenomena themselves.

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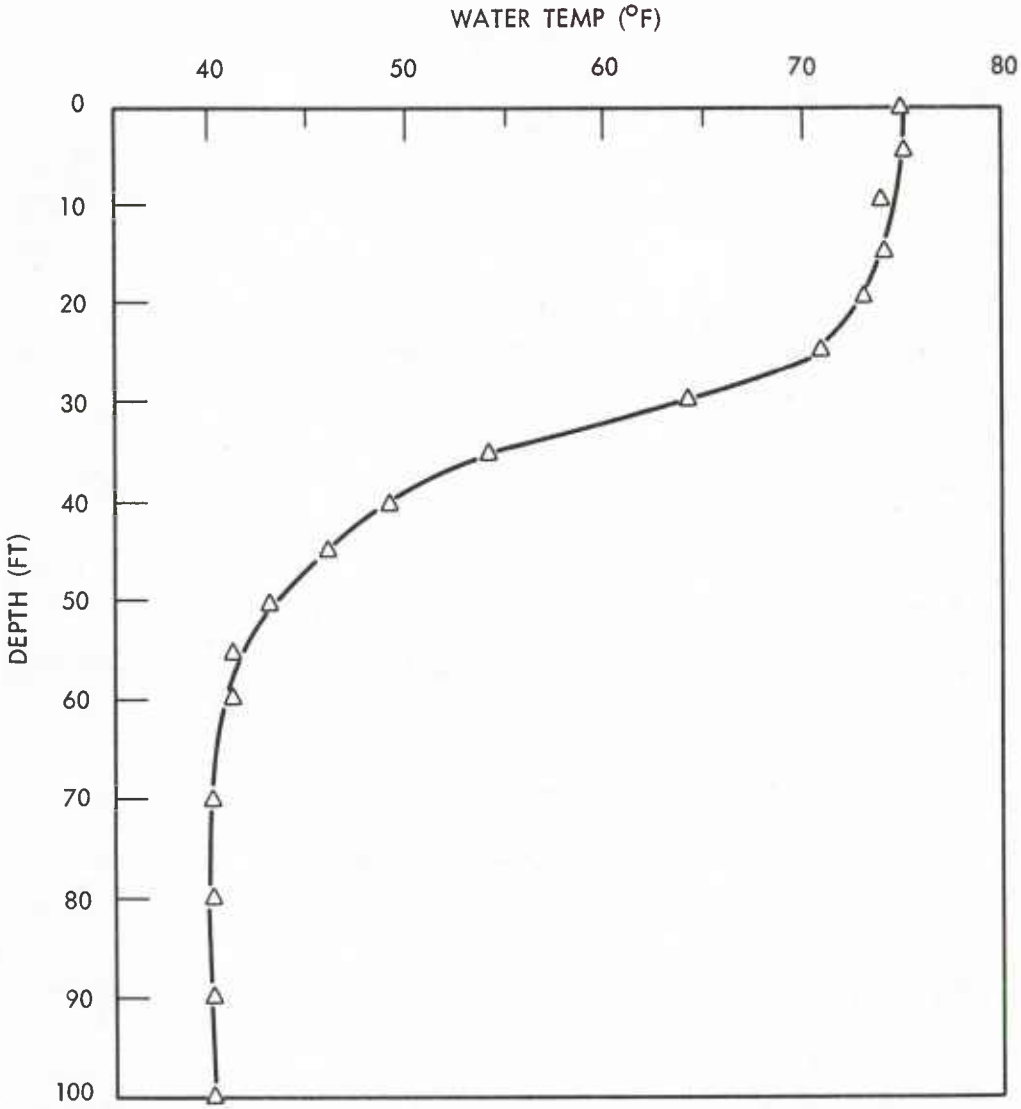

FIG. 1 MONO LAKE TEMPERATURE PROFILE

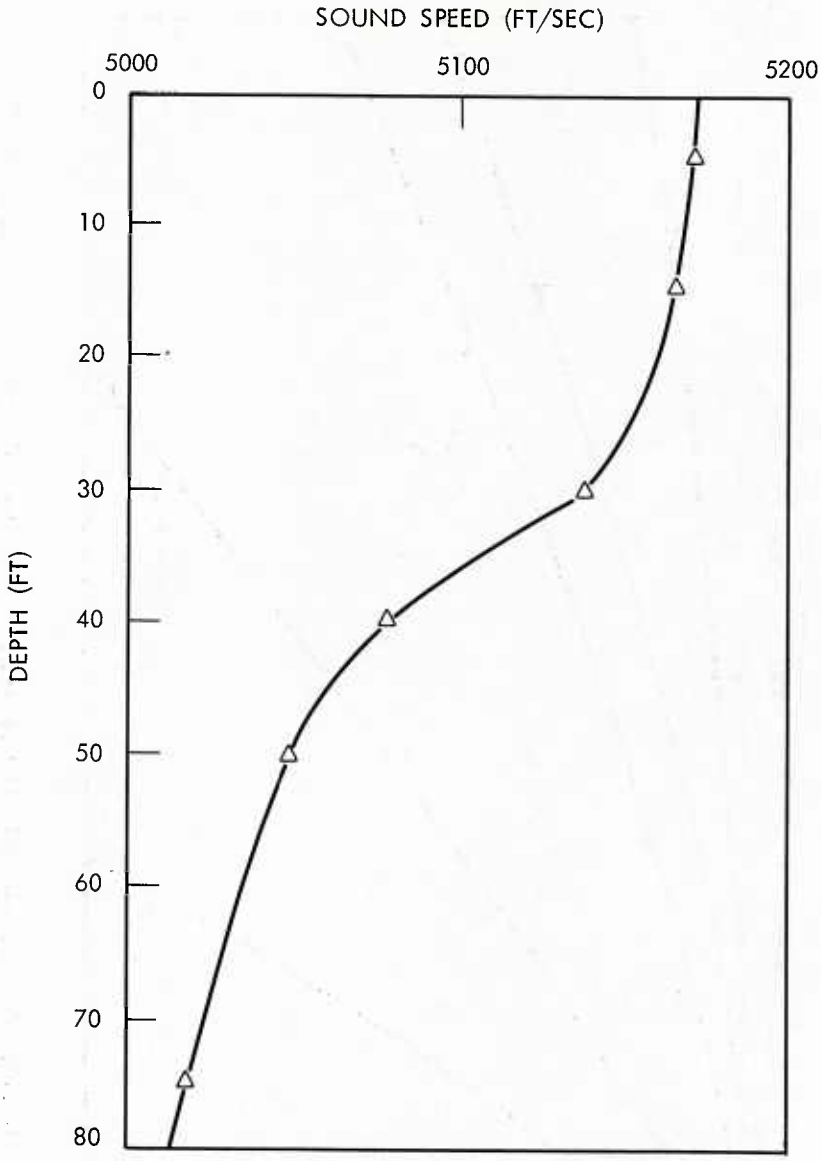

FIG. 2 MONO LAKE SOUND SPEED PROFILE

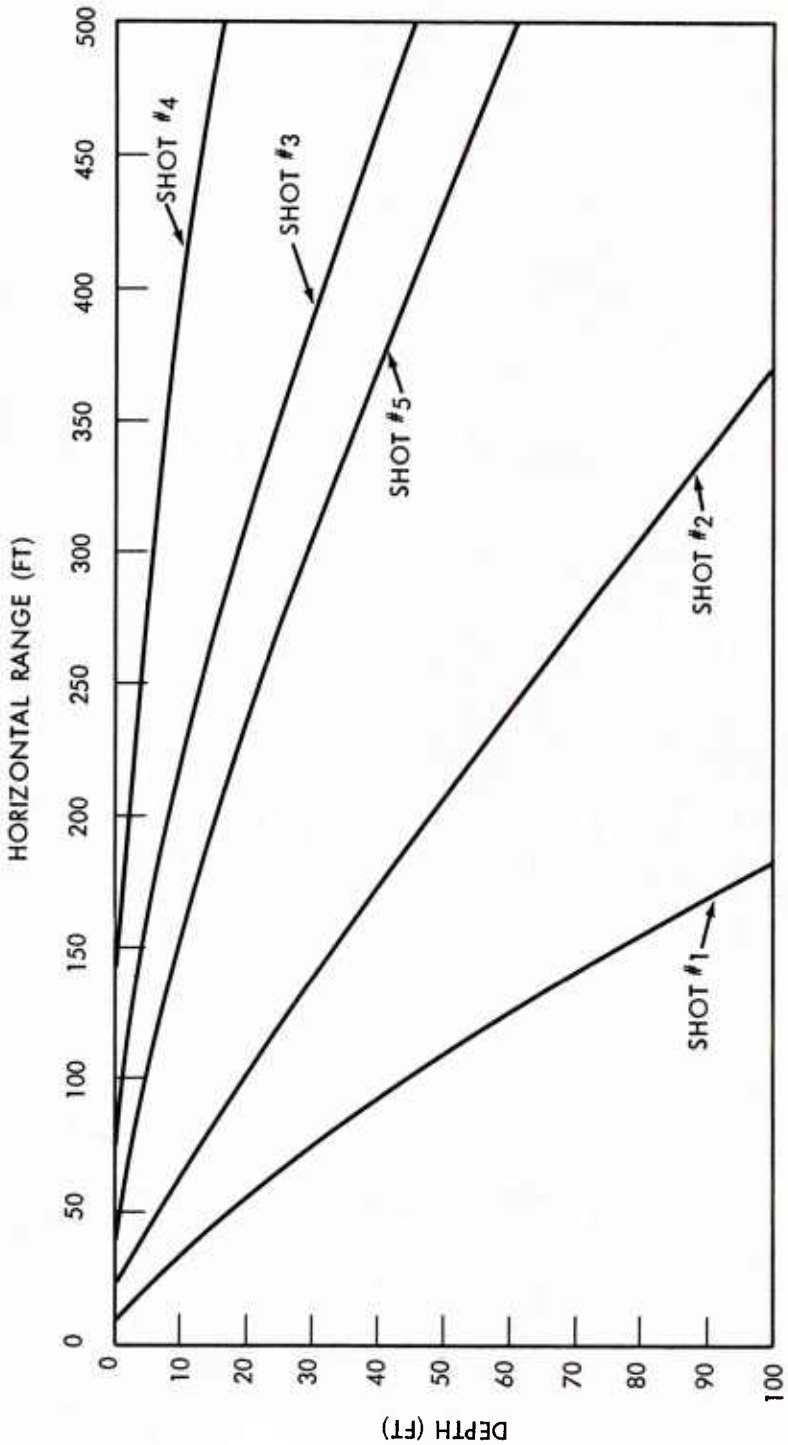

FIG. 3 BOUNDARIES OF ANOMALOUS CUTOFF REGION FOR MONO LAKE TEST GEOMETRIES

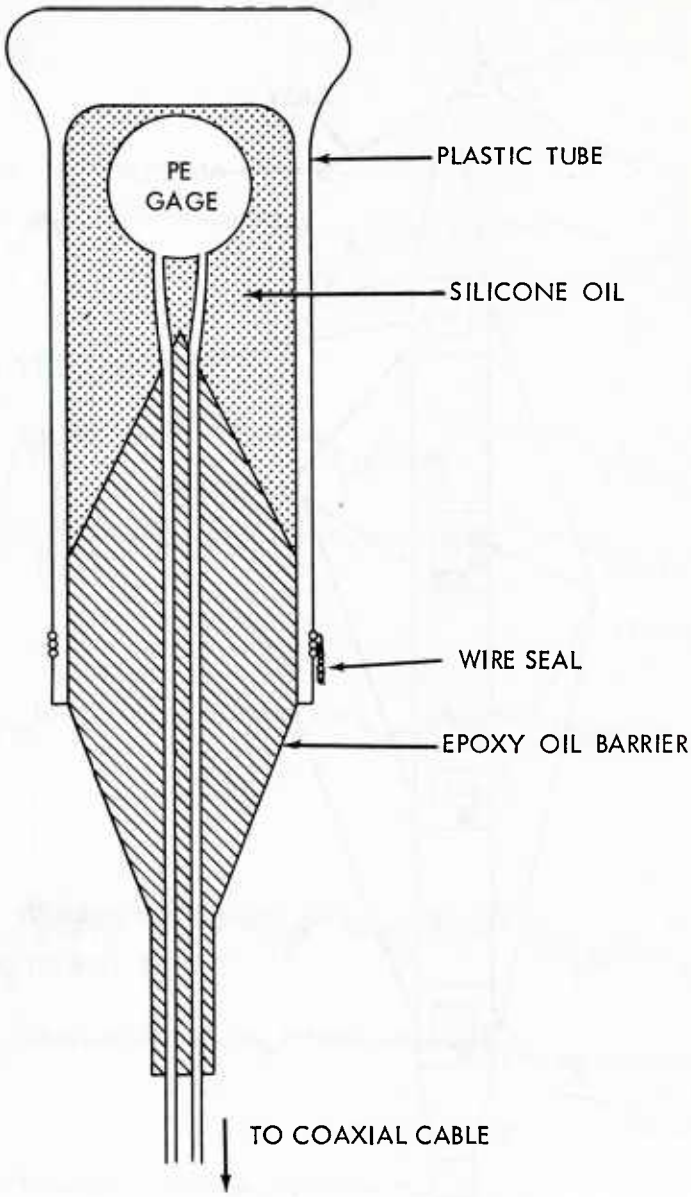

FIG. 4 WATERPROOFING CONFIGURATION FOR PRESSURE GAGES

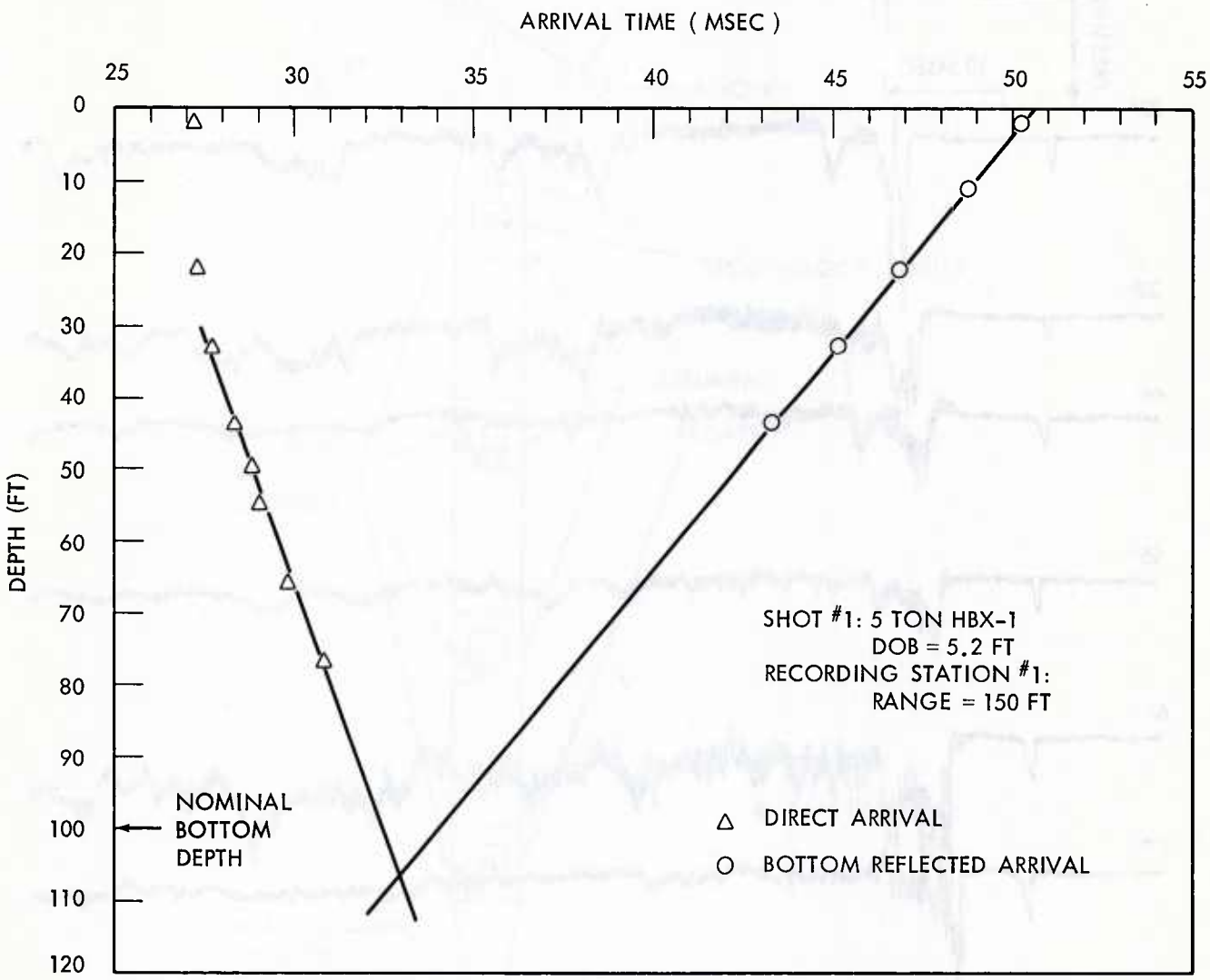

FIG. 7 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS : SHOT 1, STATION 1

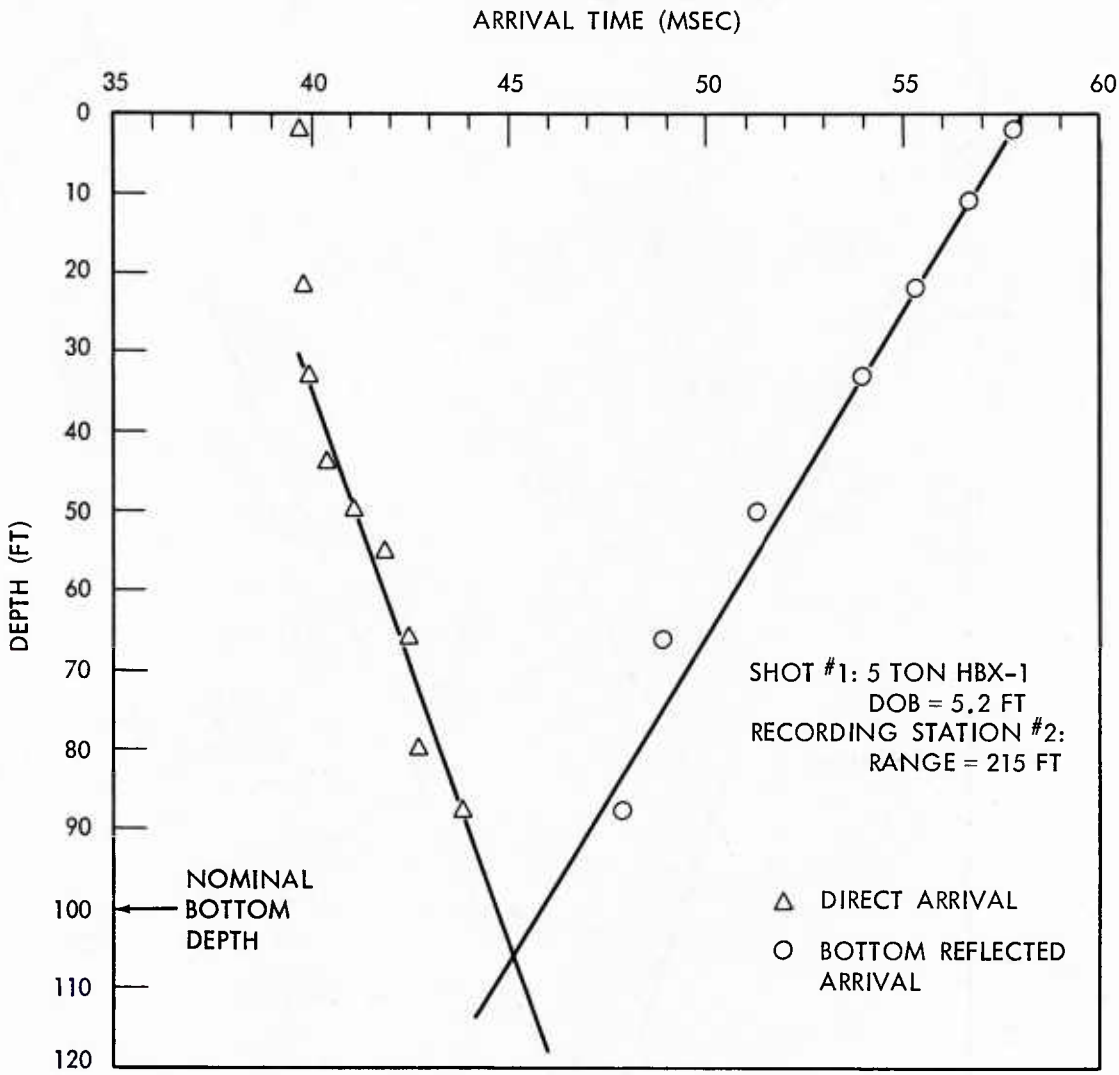

FIG. 8 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS : SHOT 1, STATION 2

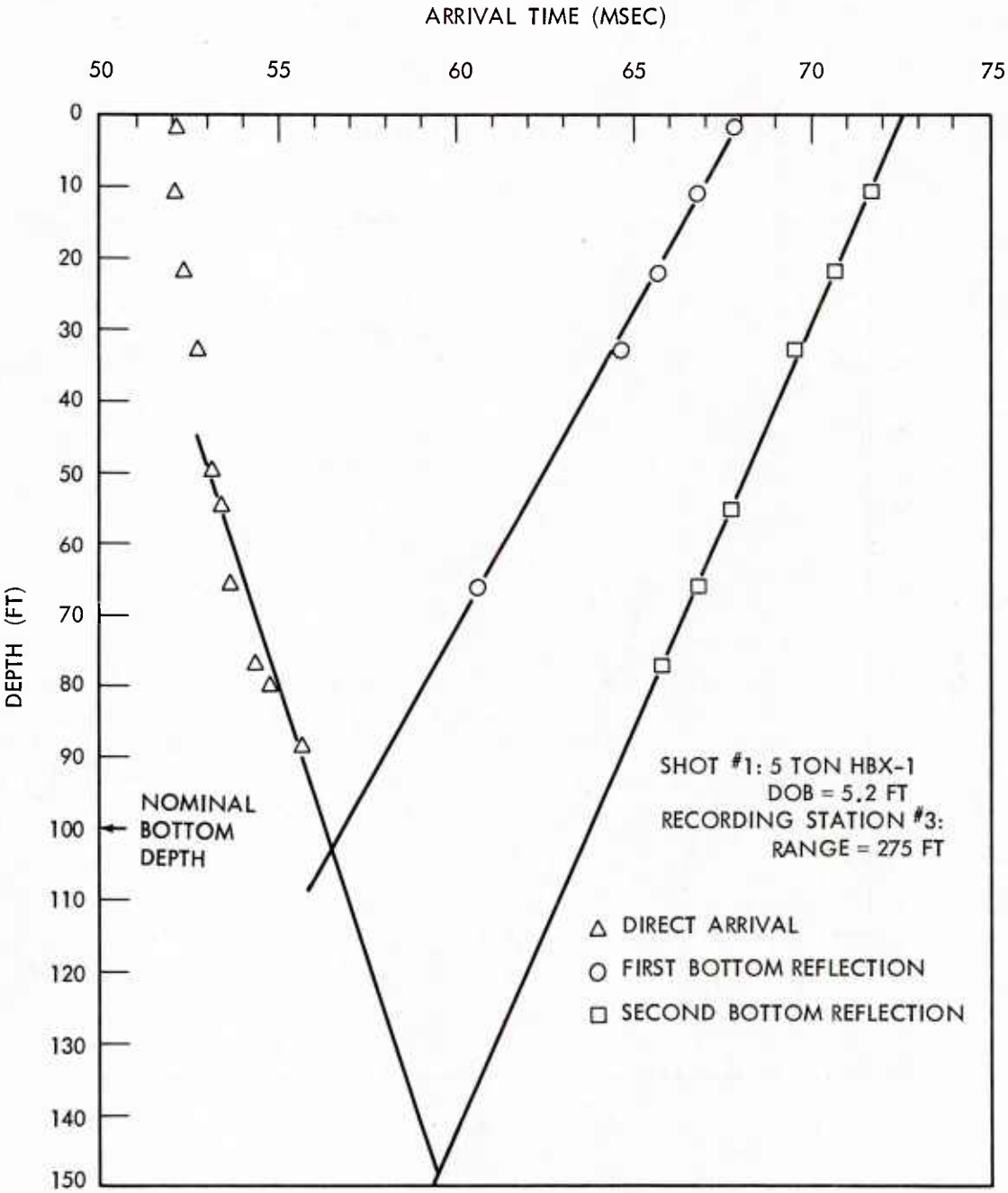

FIG. 9 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS : SHOT 1, STATION 3

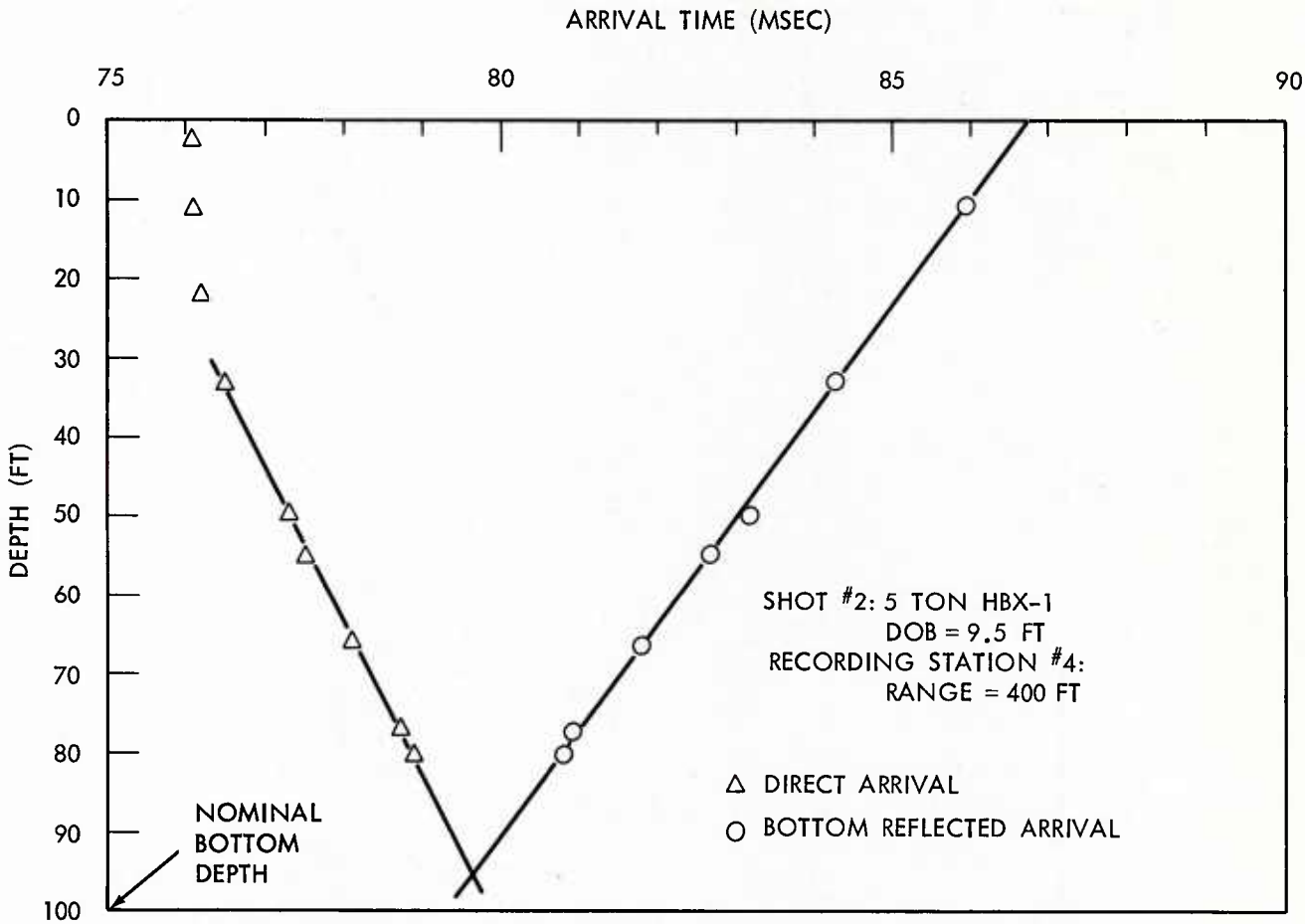

FIG. 10 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS : SHOT 2, STATION 4

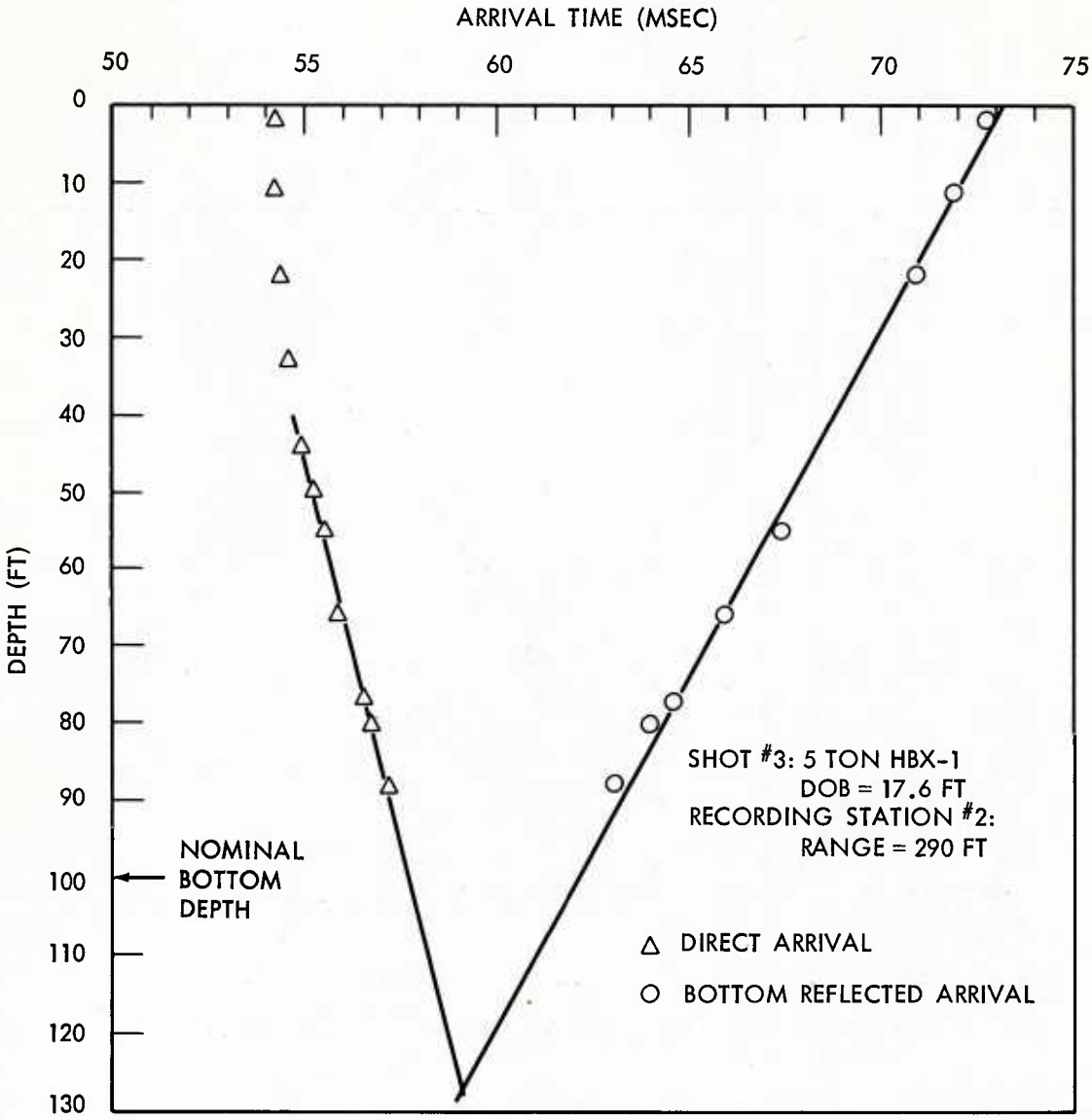

FIG. 11 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS : SHOT 3, STATION 2

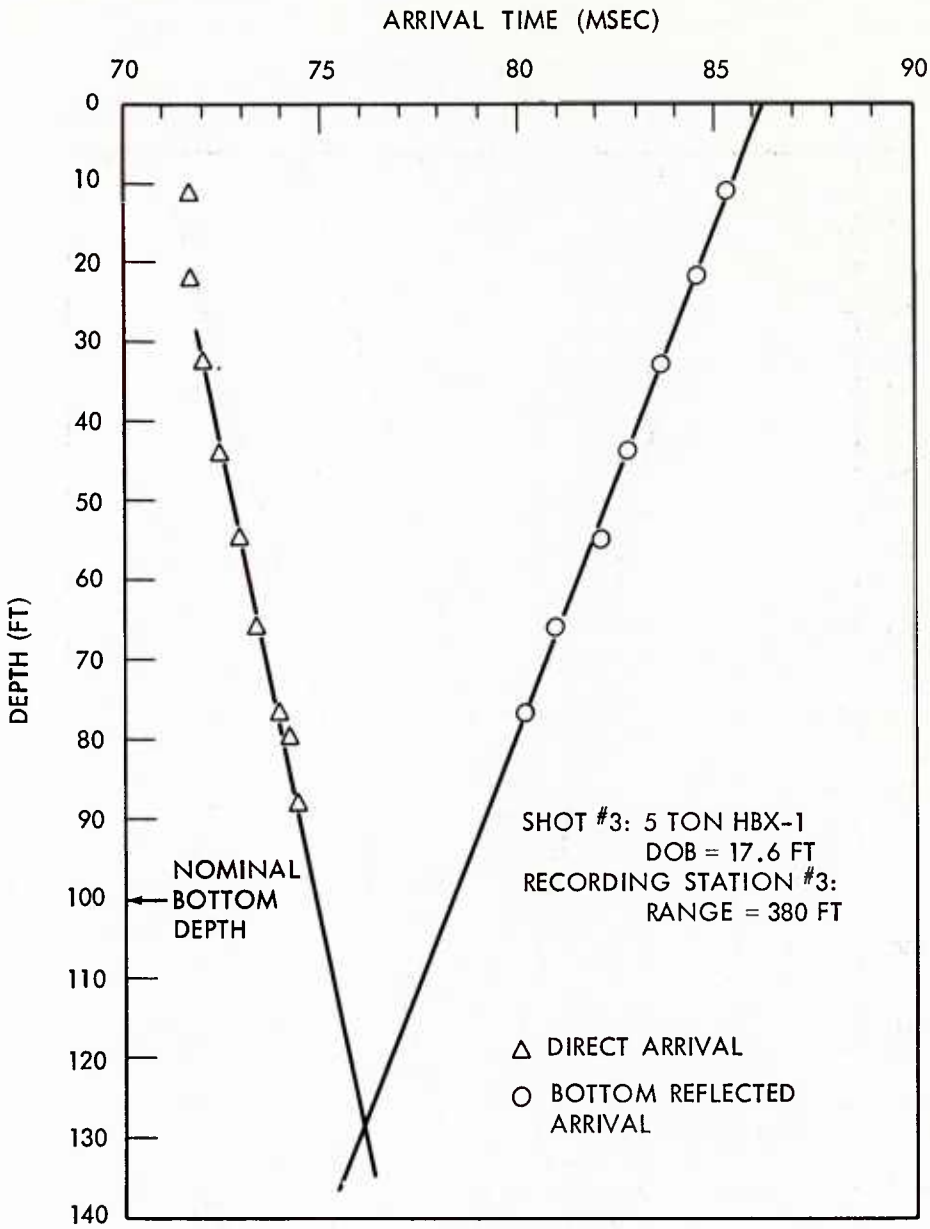

FIG. 12 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS: SHOT 3, STATION 3

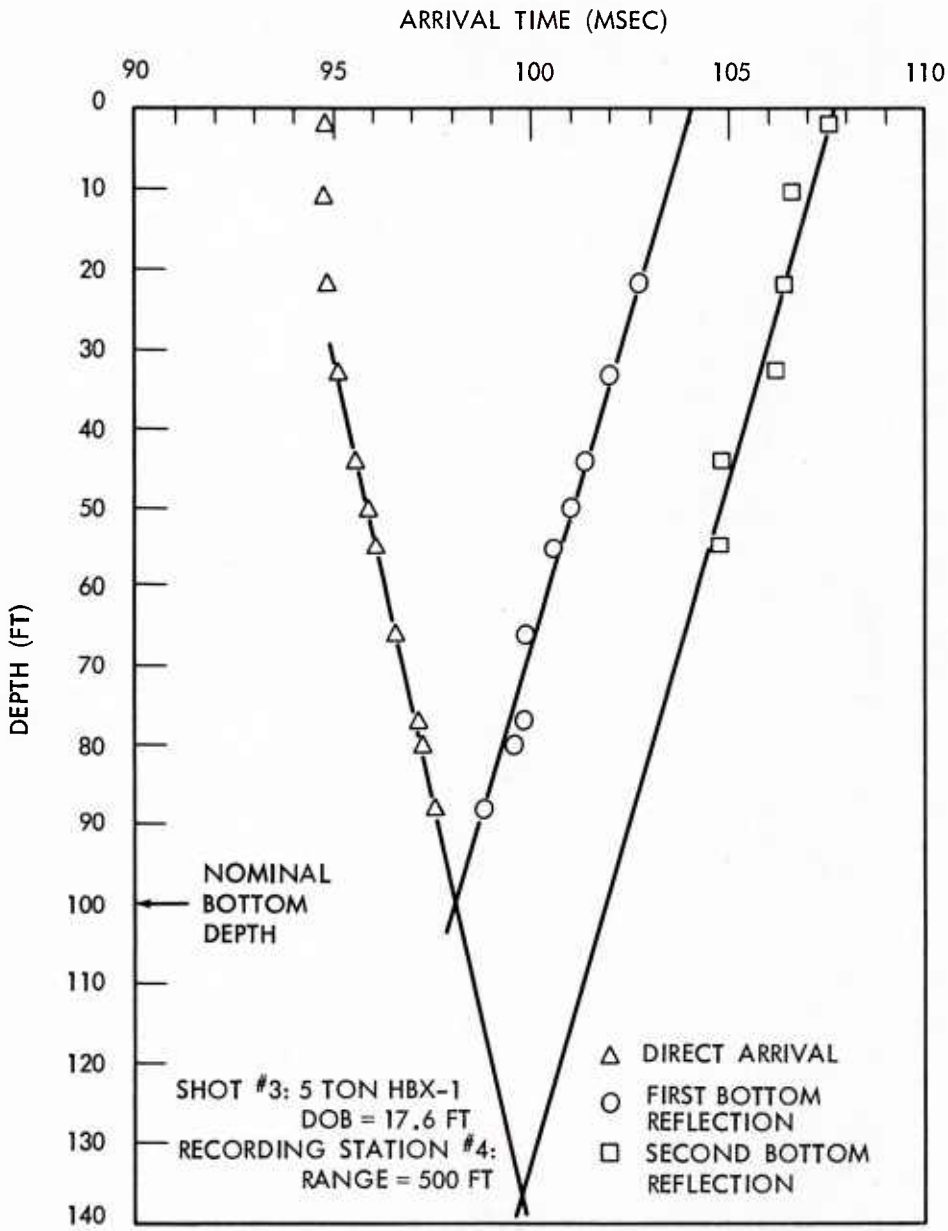

FIG. 13 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS: SHOT 3, STATION 4

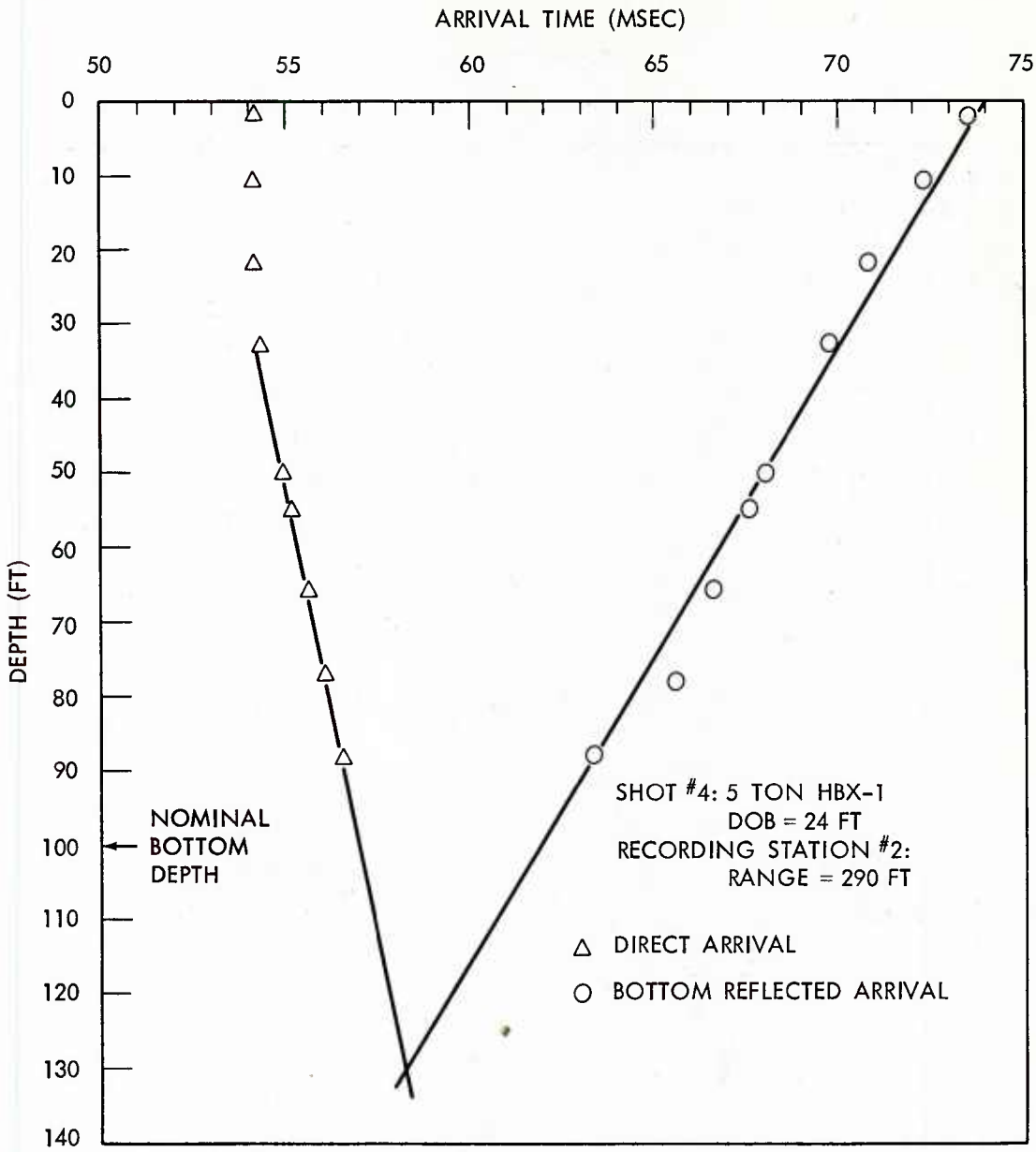

FIG. 14 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS: SHOT 4, STATION 2

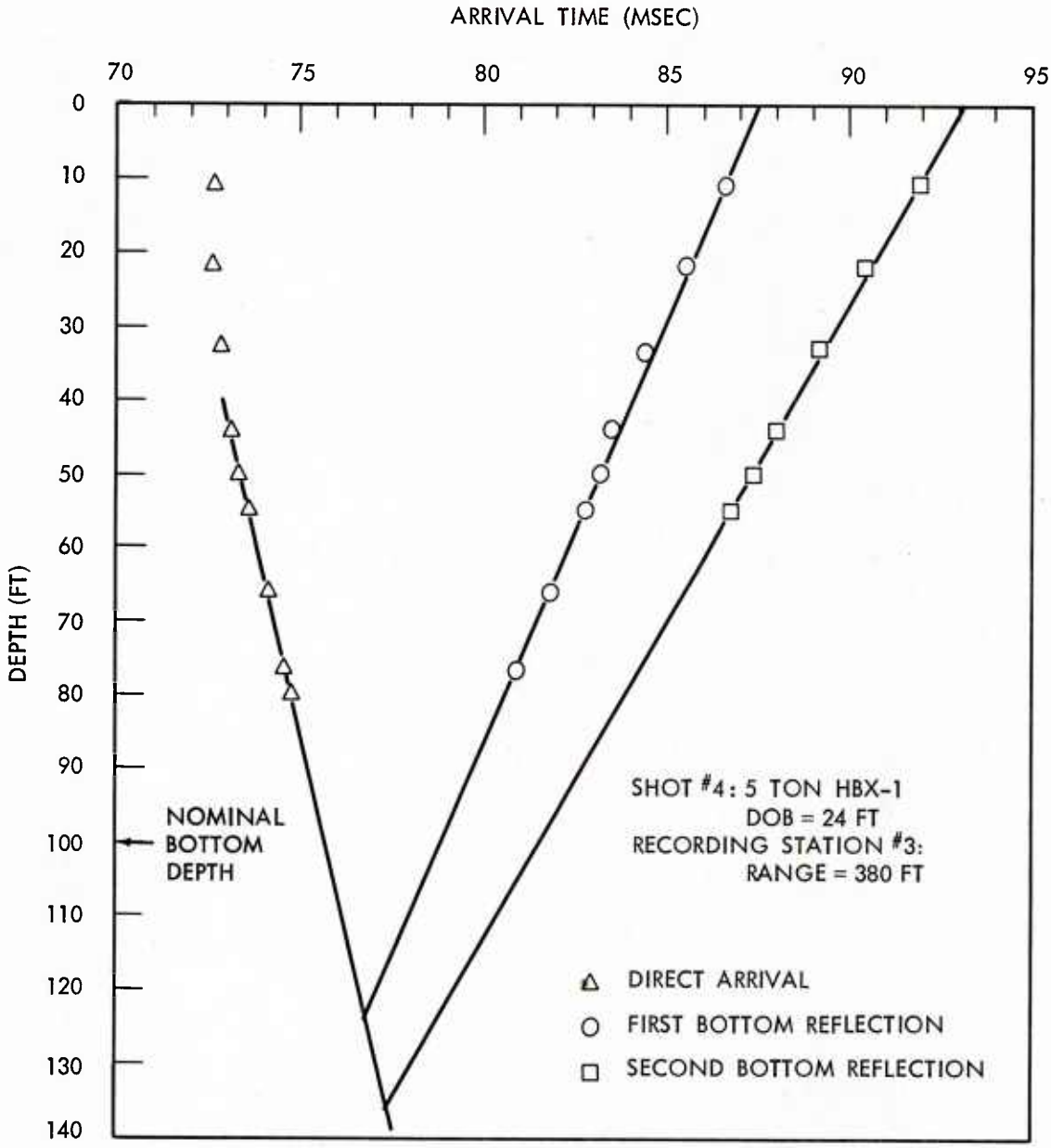

FIG. 15 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS : SHOT 4, STATION 3

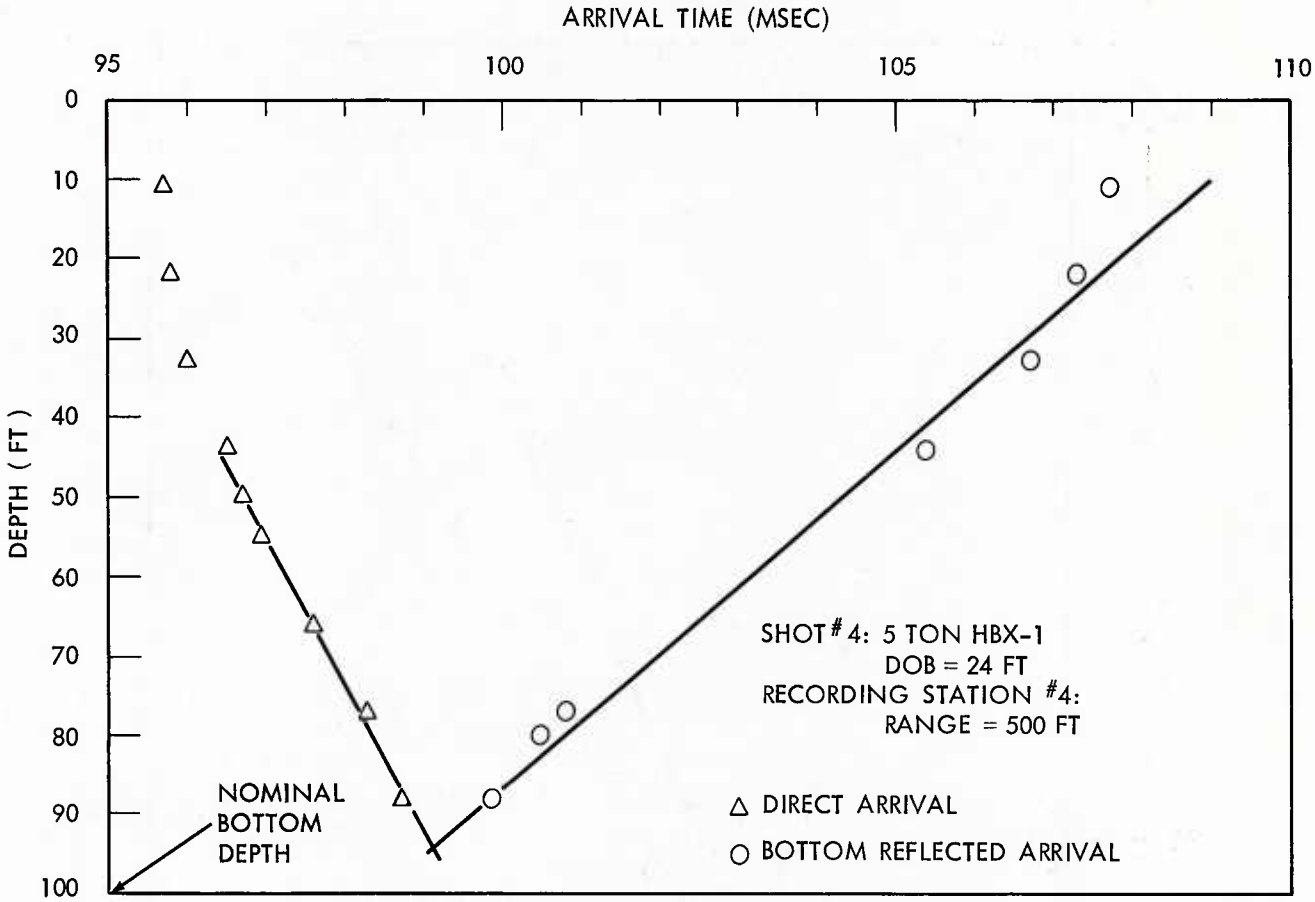

FIG. 16 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS : SHOT 4, STATION 4

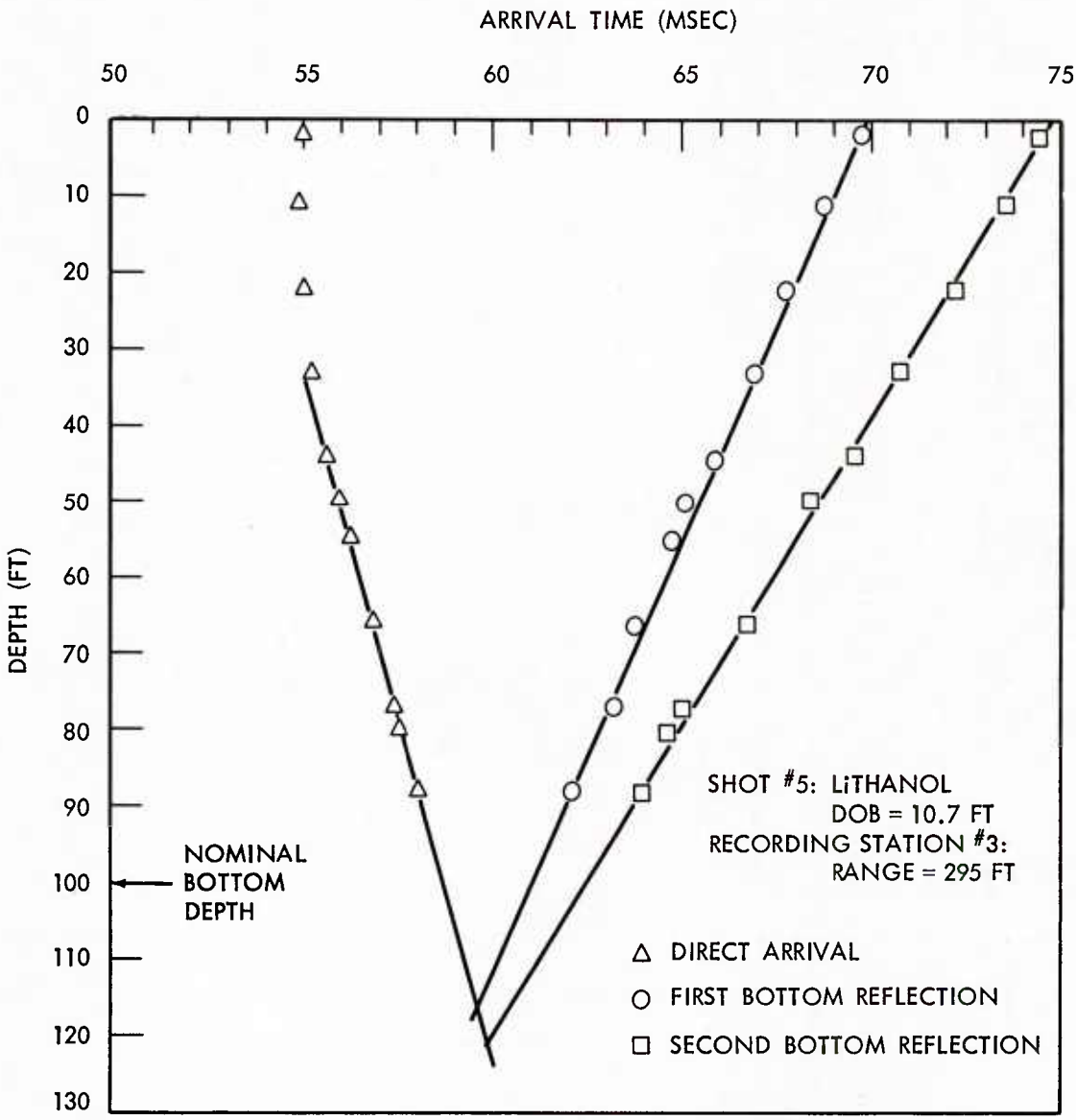

FIG. 17 TIMES OF DIRECT AND BOTTOM REFLECTED SHOCK ARRIVALS: SHOT 5, STATION 3

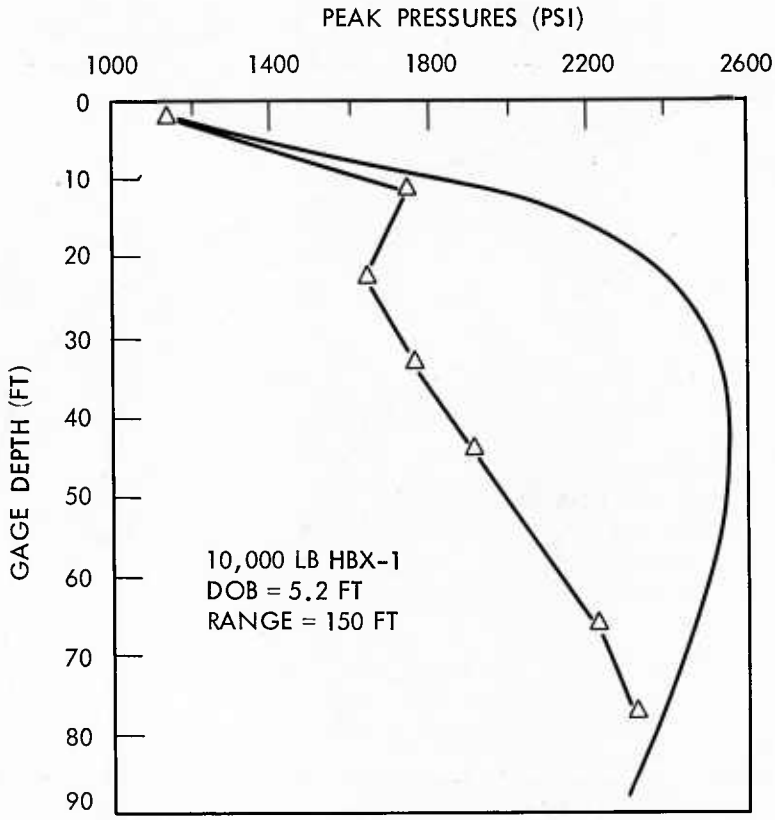

FIG. 18 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES: SHOT 1, STATION 1

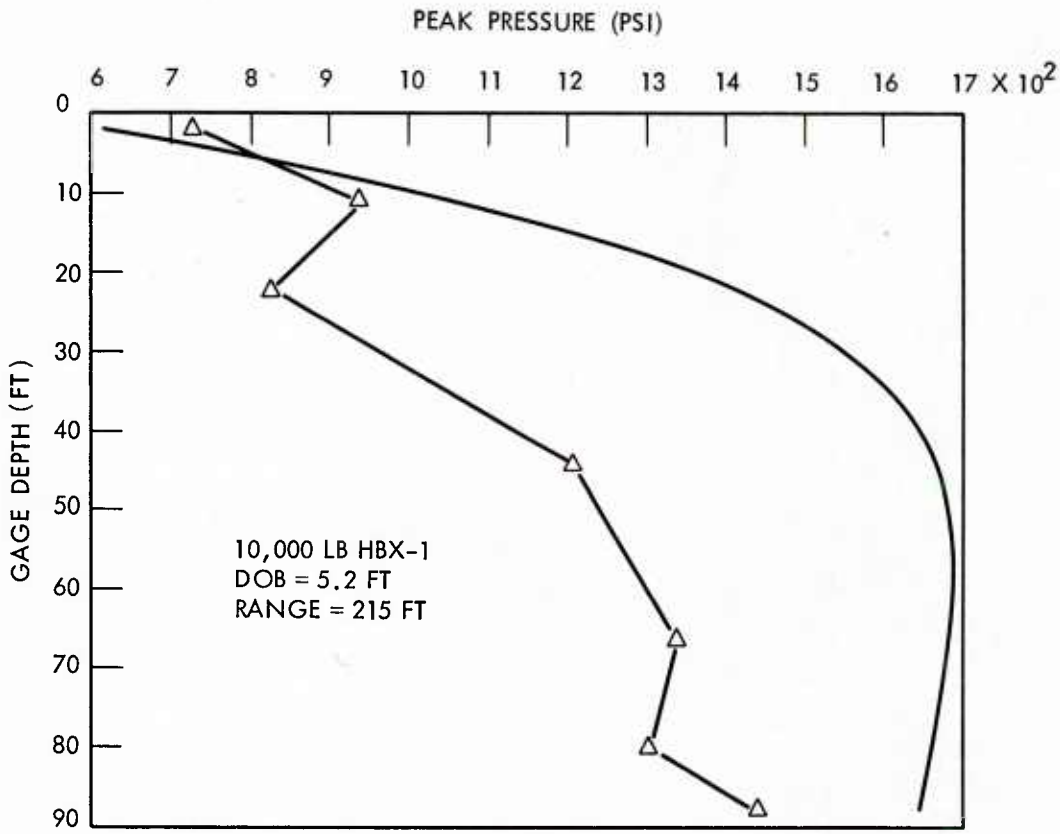

FIG. 19 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES : SHOT 1, STATION 2

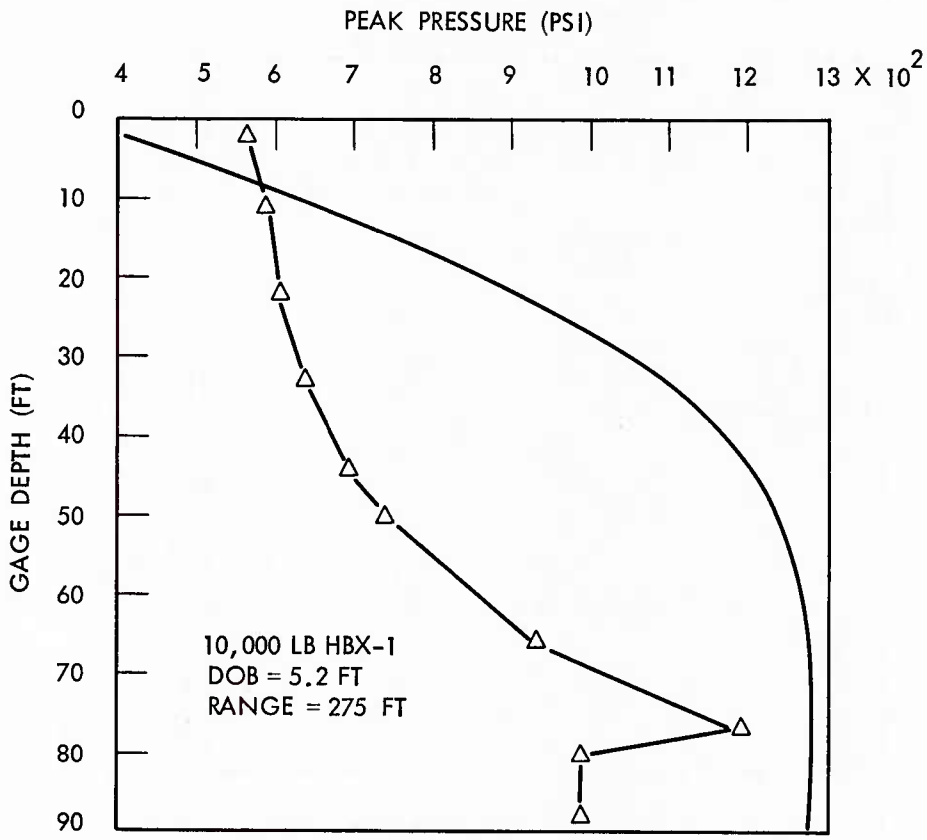

FIG. 20 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES : SHOT 1, STATION 3

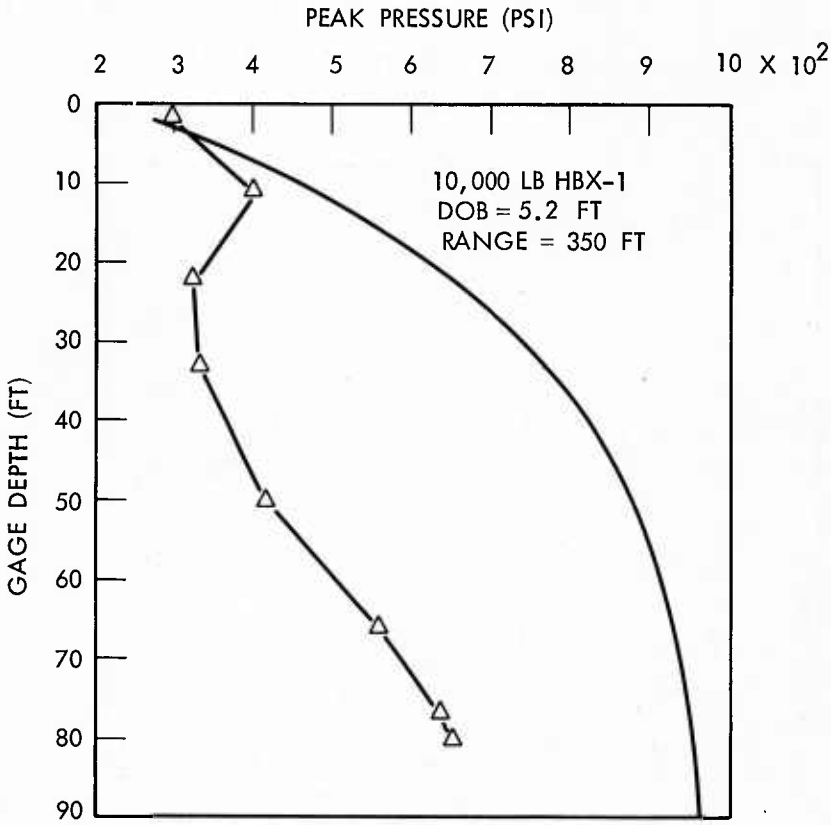

FIG. 21 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES : SHOT 1, STATION 4

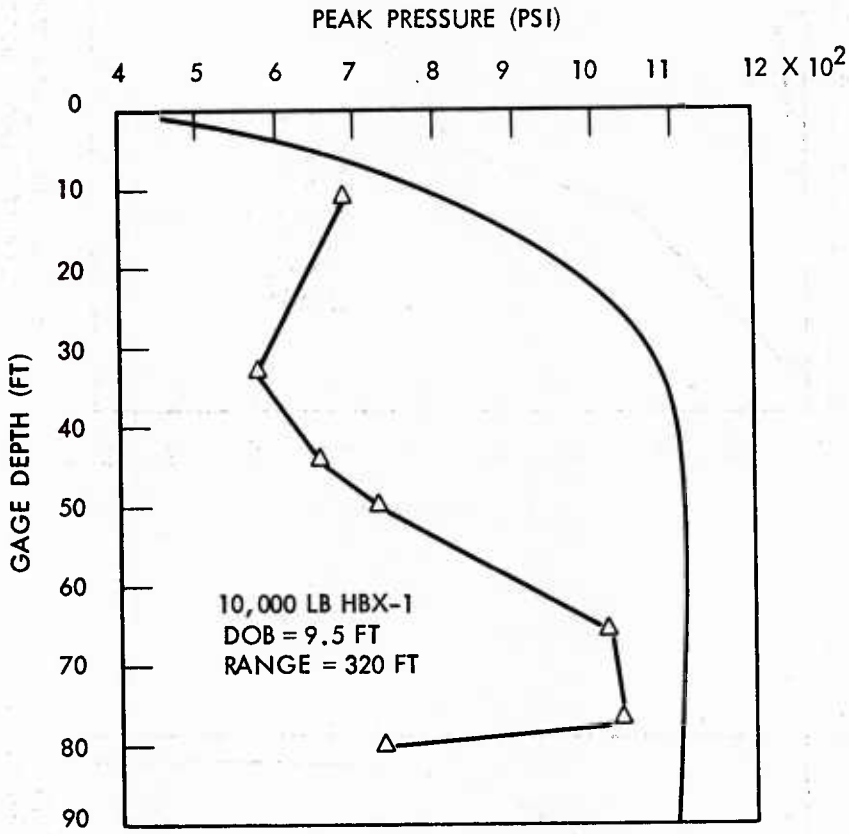

FIG. 22 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES : SHOT 2, STATION 3

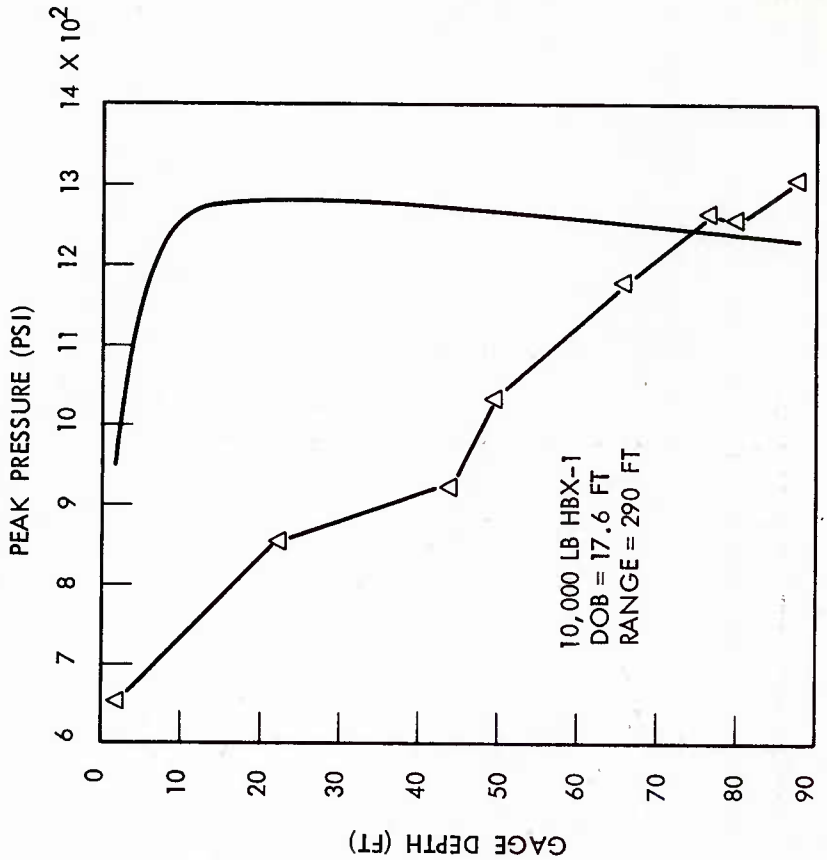

FIG. 24 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES : SHOT 3, STATION 2

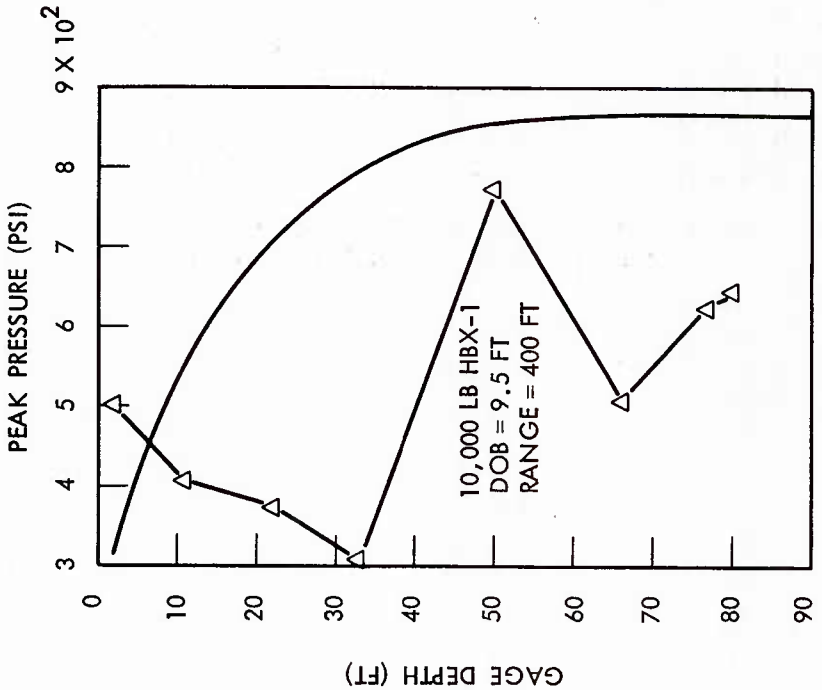

FIG. 23 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES : SHOT 2, STATION 4

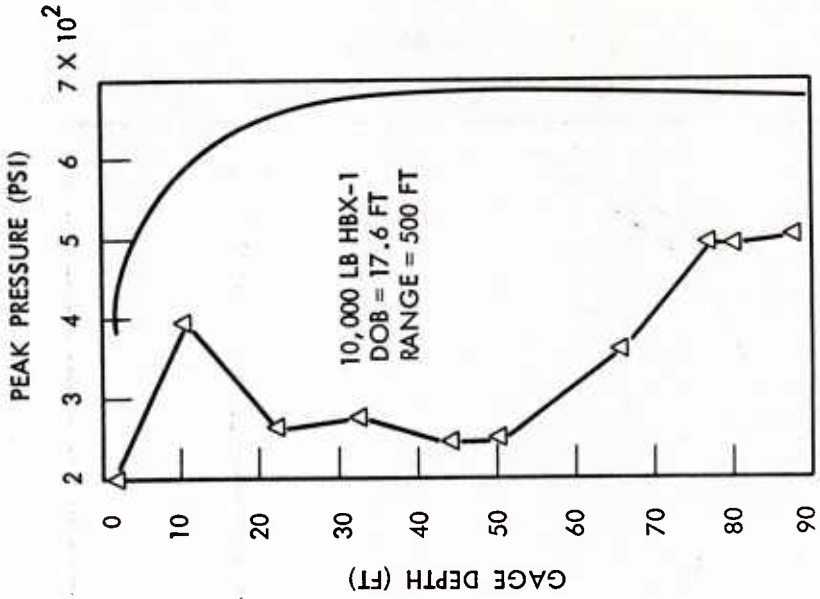

FIG. 26 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES : SHOT 3, STATION 4

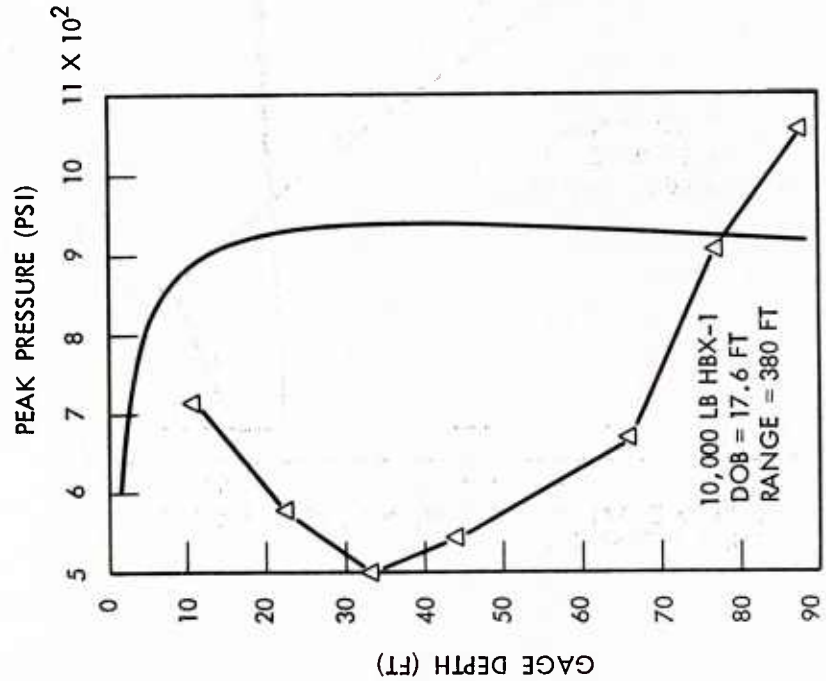

FIG. 25 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES : SHOT 3, STATION 3

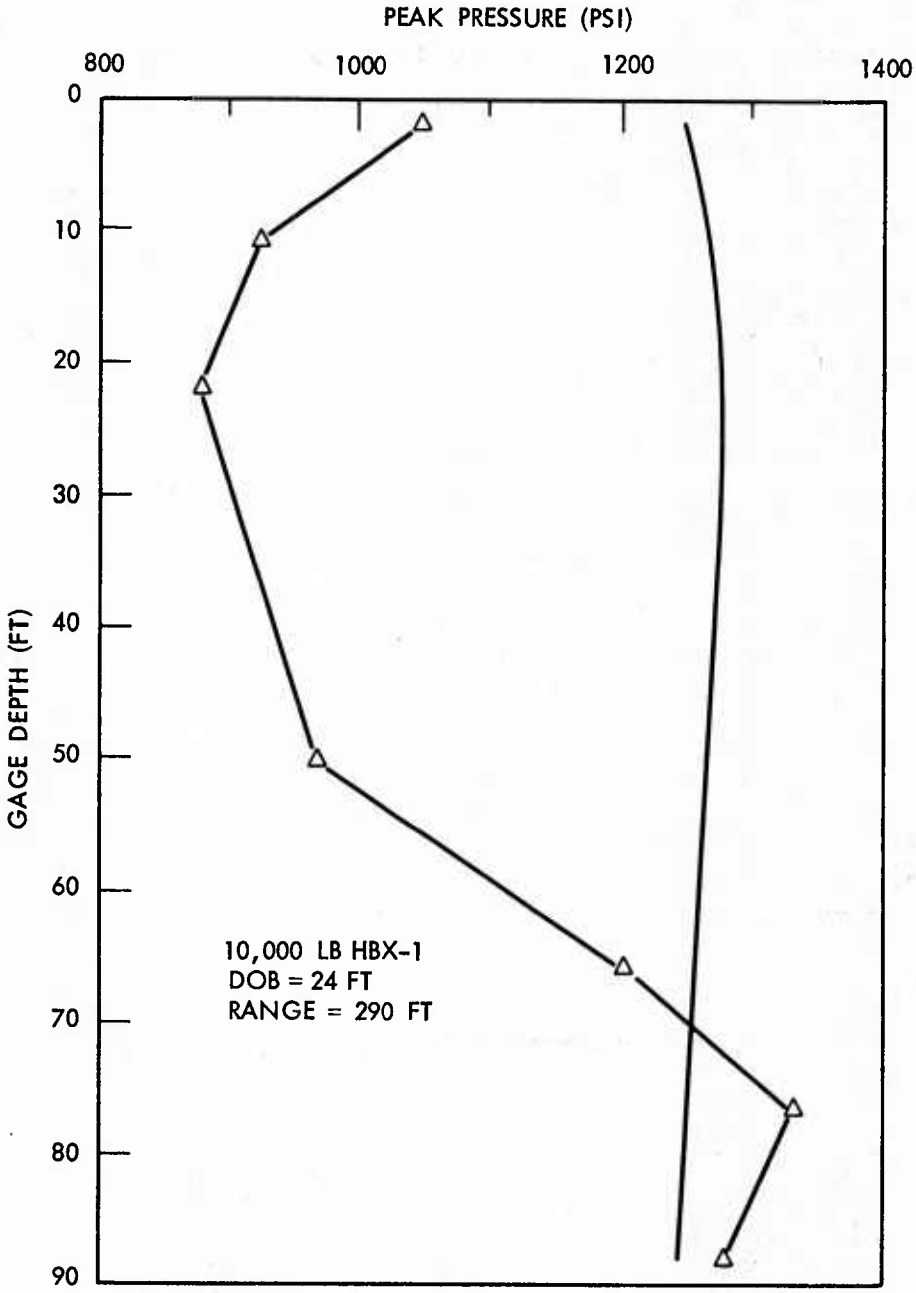

FIG. 27 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES: SHOT 4, STATION 2

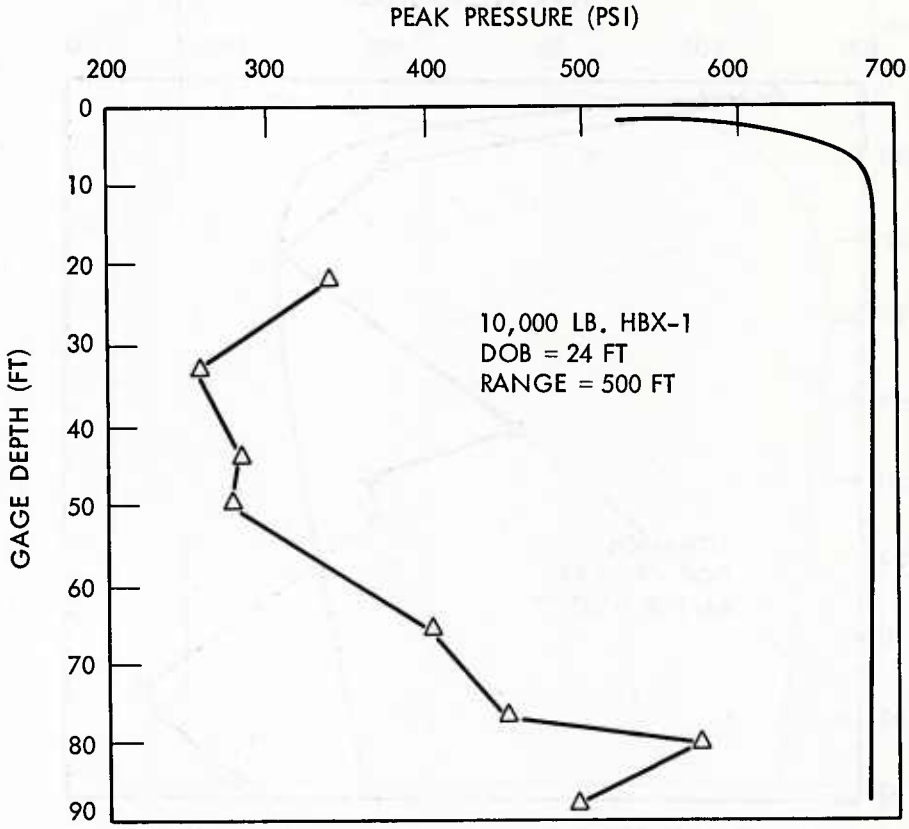

FIG. 28 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES: SHOT 4, STATION 4

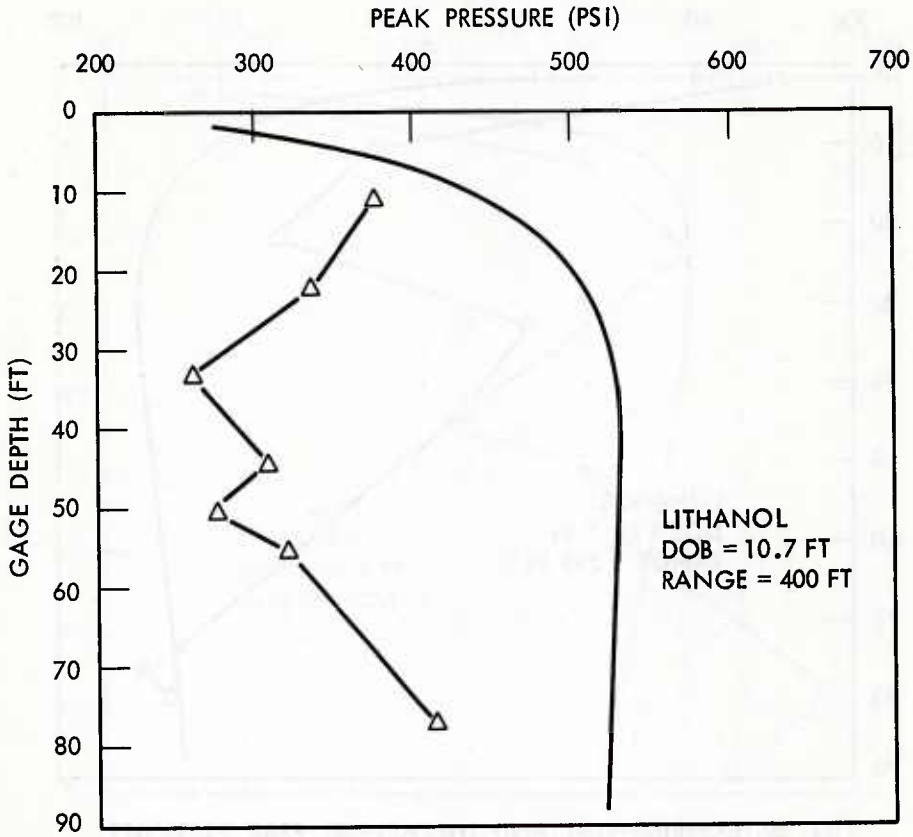

FIG. 31 EXPERIMENTAL AND THEORETICAL PEAK PRESSURES : SHOT 5, STATION 4

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