NSWC TR 88-407

16-IN. GUNBLAST EXPERIMENTS

BY DR. JON J. YAGLA

PROTECTION SYSTEMS DEPARTMENT

FEBRUARY 1989

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This report describes the blast wave from the the 16-in. naval gun. The emphasis is on the physics of the blast wave. The blast wave is described in sufficient detail to enable development of mathematical models for the loading and response of ship and equipment and to predict far field noise levels.

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FOREWORD

The work in this report was sponsored by Dr. Jerry Ward of the Department of Defense Explosives Safety Board. The experimental data reported are the result of 16-in. gunfirings conducted in support of the Battleship Reactivation Program. The experiments were conducted at the Naval Surface Warfare Center, Dahlgren, Virginia, and aboard U.S.S. *Iowa* (BB 61) and U.S.S. *New Jersey* (BB 62).

The information in this report was presented at the International Conference on Ballistics held in the People's Republic of China, 25-28 October 1988. The conference was sponsored by the China Ordnance Society and held at the Ballistic Research Laboratory/China located at the East China Institute of Technology in Nanjing.

The conference was attended by 141 ballisticians (see pages iv and v) from the United States, Denmark, France, Federal Republic of Germany, Japan, Pakistan, Poland, Sweden, and Switzerland. Also in attendance was Professor Li Hong-Zhi, President, East China Institute of Technology, where he remains an active researcher and mentor for selected graduate students. On page vi is a photograph presented to the author by Professor Li. The photograph shows the muzzle flow from a 7.62-mm rifle, fitted with a special muzzle device to create additional blast waves in the transverse direction. The photograph was taken with the new YA-16 multiflash high-speed camera, which was invented by Professor Li. The camera can take 16 pictures at computer-controlled times with a precision of 10^{-6} sec with time resolution of 0.3×10^{-6} sec. It has a resolution of 40 line pairs/mm. Professor Li received the gold medal at the Beijing International Exhibition of Inventions for the YA-16 multiflash camera.

This report was reviewed by Dr. Francis H. Maillie, Head, Ship Engineering Branch; and F. B. Sanchez, Head, Systems Safety/Security Division.

Approved by:

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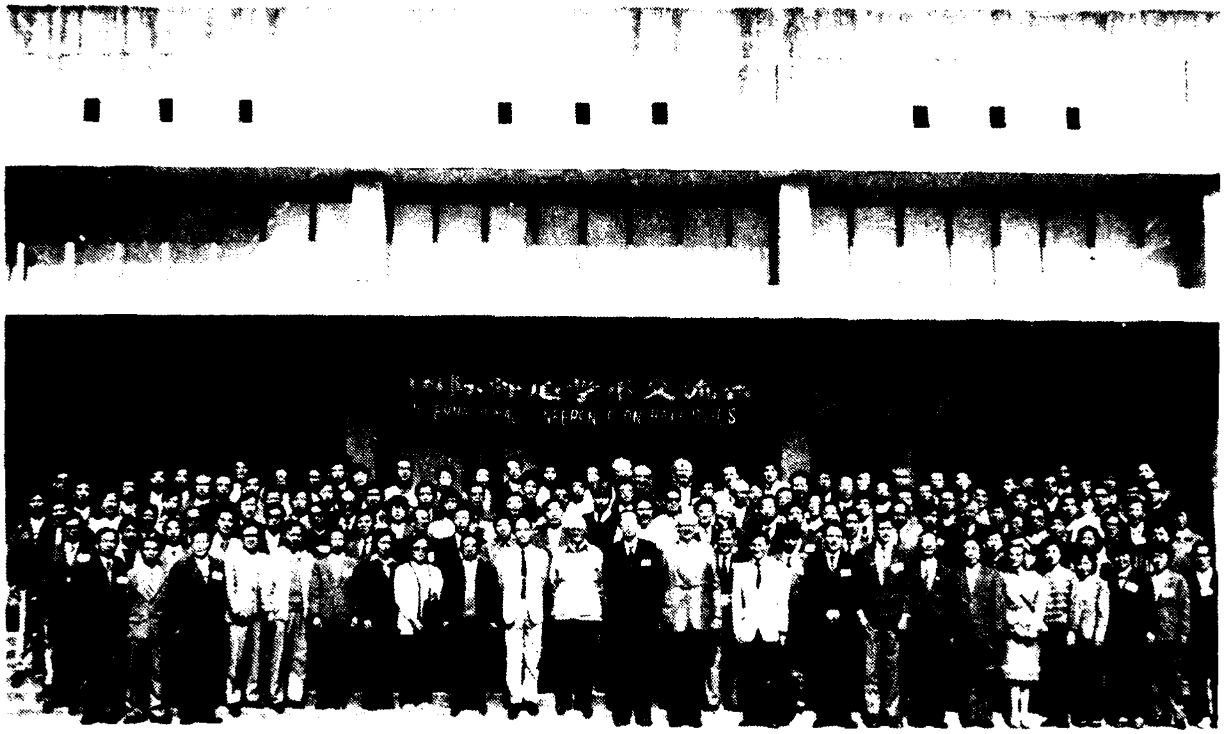

International Conference on Ballistics, People's Republic of China (25-28 October 1988)

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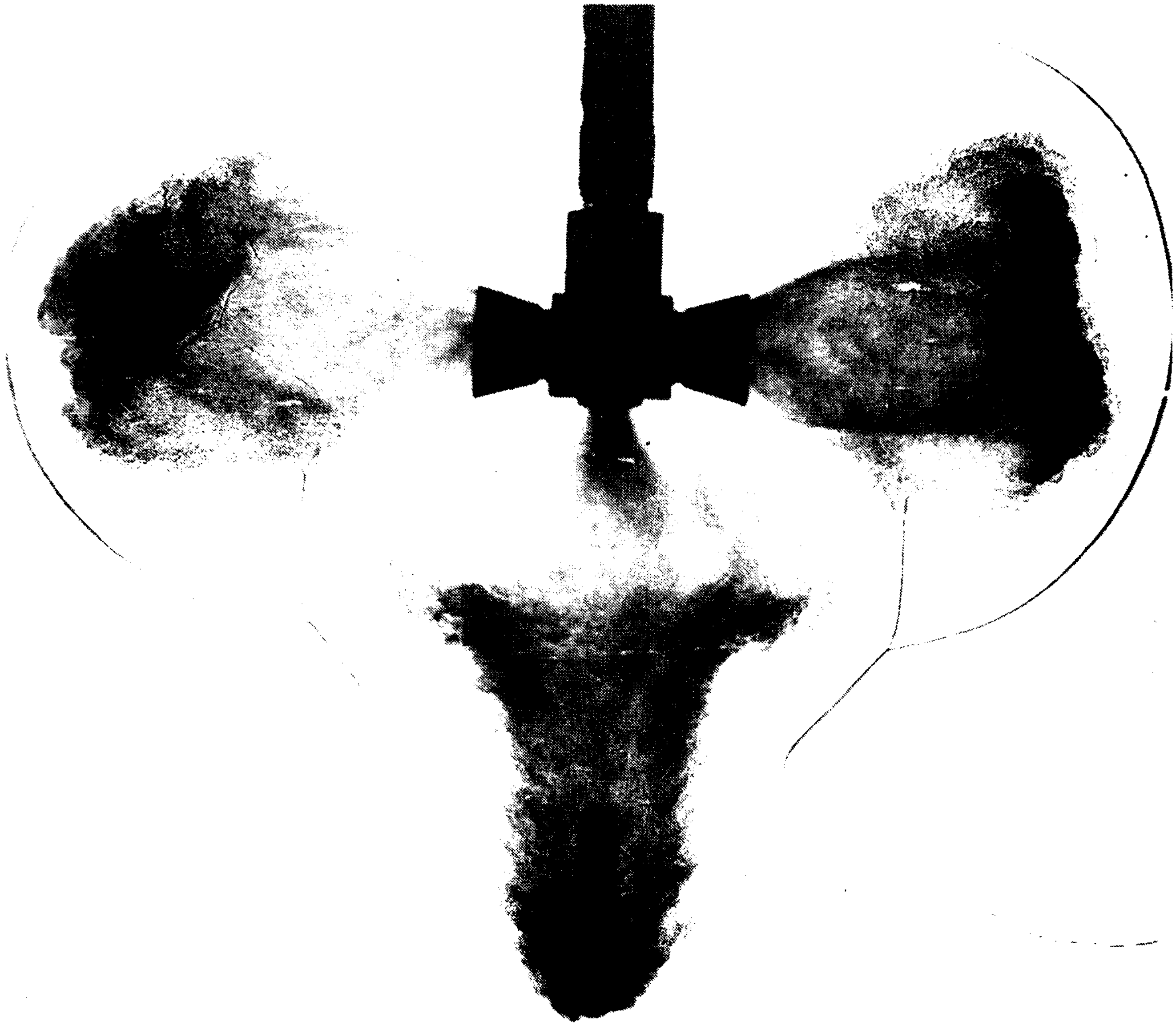

This photograph was taken with the new YA-16 multiflash high-speed camera, invented by Professor Li Hong-Zhi, President, East China Institute of Technology. The photograph shows the muzzle flow from a 7.62-mm rifle fitted with a special muzzle device to create additional blast waves in the transverse direction.

CONTENTS

INTRODUCTION

This report describes the blast wave from the 16-in. naval gun. The emphasis in this section is on the physics of the blast wave. In the following sections, the blast wave is described in sufficient detail to enable development of mathematical models for the loading and response of ships and equipment and to predict far field noise levels.

One of the most interesting of all wave phenomena is the blast wave. The blast wave is discontinuous, nonlinear, and moves through the medium at a speed greater than the speed of sound. Unlike sound waves, which all travel at the same speed, the stronger the blast wave, the faster it travels. Blast waves asymptotically approach the speed of sound as they weaken. The blast wave consists of a discontinuous jump in the thermodynamic properties at the wave front. Upon arrival at a point in space, the pressure, density, and temperature jump almost instantaneously to new values; and the medium is instantly set in motion in the direction of propagation of the wave. For example, a wave with a discontinuous jump in pressure of 10 psi travels at a speed of 1420 ft/sec (967 mi/hr). The fluid velocity behind the wave is 436 ft/sec (297 mi/hr) in the direction of travel of the wave.

Items in the path of the blast wave experience both a discontinuous change and unbalance in pressure as the blast diffracts around them and a substantial gust-like load due to the motion of the medium. A structure that may not be sensitive to the pressure load may be quite sensitive to the gust load and vice versa.

Figure 1 (see the appendix) shows the major topside weapons and equipment on the modernized U.S.S. *Iowa*- (BB 61) class battleships. Figure 2 shows *Iowa* firing a broadside with her main battery of nine 16-in. guns. Figure 3 provides a closer view of a salvo being fired from U.S.S. *New Jersey* (BB 62).

Figure 4 shows a blast wave leaving a 16-in. gun barrel. "Section view" representations are shown of the blast wave in the horizontal plane at two times after gunfiring. The wave is nearly symmetrical about the gun axis and has a distended spheroidal shape. The radii along the axis are longer, and the radii behind the gun are shorter. The pressure is shown as the measure of strength of the waves. There is a short period of negative overpressure and negative velocity that is not shown in the diagrams. The wavelets are drawn to scale from data obtained through experimental 16-in. gunfirings at the Naval Surface Warfare Center (NSWC), Dahlgren, Virginia.

A blast wave from a 16-in. gun as it approaches the forward Close-In Weapons System (CIWS) sponson on *New Jersey* is shown in Figure 5. Again, the wave is drawn to scale from experimental data. The wave would diffract around the CIWS, then reflect off the ship's bulkheads. The reflections would then load the equipment on the sponson from behind. The intensity of the blast wave at the CIWS governs the allowable firing arc of Turret No. 2.

A detailed experimental investigation of 16-in. gunblast was carried out to design firing zones for the battleships and to develop improvements for battleship equipment. The experiments were carried out with a 16-in. gun at Dahlgren, on *Iowa*, and on *New Jersey*.

BLAST EXPERIMENTS WITH A 16-IN. NAVAL GUN

The initial experiments for the Battleship Reactivation Program were conducted at the Dahlgren range, which consists of 20 miles of open water on the tidal Potomac River, 50 miles south of Washington, D.C. The gun line has a single 16-in./50-caliber gun mount that was used to conduct the experiments. Pressure data were taken at 34 locations around the gun.

The first set of experiments was conducted to obtain "near field" data and measured blast overpressures out to distances of 200 ft (2 psi) from the muzzle. This is the region of interest for shipbuilding and equipment design. Further experiments were conducted to measure the "far field" propagation out to distances as far as 28 miles.

Three different arrangements of the instruments were used for conducting the firing. Twelve rounds were fired with each instrumentation array. The first array used 10 transducers along the 45-, 75-, and 125-deg radials. The second array used 13 transducers located along the 60-, 90-, and 150-deg radials. The third array used 13 transducers along the 15-, 30-, and 105-deg radials. The instrumentation is shown in Figures 6 and 7.

The battleships employ several types of 16-in. ammunition. Full propellant charges or reduced charges can be fired. The full charge consists of 660 lb of smokeless propellant. The reduced charge consists of 330 lb of propellant. Reduced charges have the advantage of better accuracy (due to more consistent initial projectile velocity) and less wear on the gun. There are two weights of projectiles in use, 1900 and 2700 lb. In an operational situation, the type of charge and projectile is selected based on the characteristics of the target, the range, and what is available in the magazine.

A second purpose of the 16-in. gun experiments was to measure the performance of 16-in./45-caliber propellant and to determine the effect of projectile weight. There are no 16-in./45 caliber guns left in naval service, but a large quantity of propellant had been saved. SPD-9606 and SPDN-10494 propellants for the 16-in./45-caliber gun and 16-in./50-caliber gun, respectively, were employed. The 1900-lb high capacity (HC) and 2700-lb armor-piercing (AP) projectiles were used. These variables, plus relocating the instruments every 12 rounds and adjusting the 16-in./45-caliber propellant charge in the course of the experiment, created a considerable database that required a formal statistical analysis. Reduced charges were not used in the experiments.

Statistical tests of the database showed that the normal round-to-round variation in blast overpressure exceeded the variation due to propellant type and projectile weight. The data from all 36 rounds were then analyzed as though the experimental conditions were constant. The good agreement with later data from *New Jersey* and *Iowa* justified the approach.

A complication arose in analyzing the data. The 16-in. gun propagates damaging overpressures over such distances that the effects of the ground surface in front of the gun could not be neglected. Figure 8 shows the 16-in. gun firing horizontally. The blast wave soon arrives at the surface and reflects upward. Initially the reflection pattern is "regular," although the angle of incidence for the nonlinear wave is not equal to the angle of reflection. After a critical angle of incidence, the pattern changes to Mach reflection, where the incident wave and the reflected wave are connected to the reflecting surface by a third wave called the Mach stem. Many of the outer instruments were located in the Mach reflection region. The data from these locations could not be used to predict free field overpressures until adjustments were made.

The correction procedure was developed as follows. The blast felt at a distant point, such as "P" in Figure 8, would be equivalent to the blast from the real gun, if it were fired in free air, plus the blast from a virtual gun fired in free air from beneath a plane of symmetry. The total propellant fired would be twice the service charge. If this larger charge were fired out of a single larger gun in free air in the plane of symmetry, the same blast would be felt at "P." So the blast at "P" measured in the experiment is equivalent to the blast that would have been measured in free air from a correspondingly larger gun.

To a first approximation, all guns are scale models of one another and so are their blast fields.[1] If the larger gun would be $2^{1/3}$ times as long and $2^{1/3}$ times the diameter as the 16-in. gun, then its chamber would have twice the volume and fire twice the charge. The pressure at "P" should therefore be plotted at a new distance reduced by the factor $2^{-1/3}$. For example, the data from instruments at 200 ft were all in the Mach stem, and are therefore plotted at a reduced distance of 159 ft. The data from the various radials are plotted in Figures 9 through 17. Also plotted in the figures are a number of scattered points that were measured at various locations in the *New Jersey* experiments.[2,3] It is apparent that the 16-in. gunblast is not precisely repeatable.

The detailed structure of the blast wave was studied through careful measurements of high-speed photographs of blast waves taken during experiments at Dahlgren and firings from *New Jersey*. The blast wave was clearly visible in some of the films. The film images were projected onto a large screen overlay, and the shock wave was carefully drawn for each frame in the motion picture sequence. The projectile was also visible in each frame of the sequence. Its speed was measured during the experiments with a Doppler effect radar velocimeter, and the speed and projectile location were used to calibrate the images. The images were then digitized for input to a Computervision CADD (computer-aided design and drafting) drafting system. The shock wave propagation from the muzzle is shown in Figure 18. The techniques employed in the analysis are explained in detail in Courter.[4]

The field line method,[5] was used to further analyze the data stored in the Computervision system. With the field line method, one constructs a manifold of the orthogonal trajectories of the shock front. The orthogonal trajectories thus computed are called the field lines. The shock can be thought of as propagating along the field lines. Numerical differentiation along the field lines provides velocities that can be used in Rankine-Hugoniot equations to calculate the pressure behind the shock front. The field lines for Figure 18 are shown in Figure 19. A seventh-order spline curve-fitting routine was used to generate the shock wave profiles. The field lines were constructed by using an iterative shooting method for projecting field line segments from the shock wave. In regions of significant curvature, the field lines were also constructed with the use of splines.

The motion of the interface (contact surface) between the expanding propellant and the shocked air was also studied. The geometry of the contact surface is very complicated due to instability and turbulence. The method of characteristics was used to compute properties of the flow between the shock wave and the contact surface. The field line data or pressure sensor data can be used to form a non-characteristic line of initial values. The method of characteristics can then be employed to compute the density, pressure, and sound speed distribution between the shock and the contact surface. Method of characteristics calculations were carried out, as described in Courter.[4]

The calculations were not completely successful due to problems with the data. However, several important conclusions were possible. First, the blast wave does not propagate as predicted from simple expanding piston models. Rather, it both accelerates and decelerates several times during the early development of the flow. The trajectories for 0-, 30-, and 45-deg radials are shown in Figure 20. The inflection points on these curves indicate a speeding up of the contact surface and shock wave. This is only possible through additional energy being added to the flow. We believe that combustion in the turbulent mixing region at the interface is an important energy source and leads to the phenomena of a flash-driven blast wave. Second, observations and photographs of numerous 16-in. gunfirings show that each fireball is different and that the fireballs are not symmetrical about the gun axis. This is believed to be the main reason for the round-to-round statistical variation in the blast data from the 16-in. gun.

Analytical expressions for the peak overpressure in the blast field were developed from the plots in Figures 9 through 17. The simplest expression one can hope for is of the form

$$P = A(\theta)r^{-\alpha(\theta)} \qquad (1)$$

where P is the overpressure in psi, $A(\theta)$ and $\alpha(\theta)$ are functions of the azimuth angle, θ; and r is the distance measured from the gun. The coefficient, A, determines the directivity; and the exponent, α, gives the rate of decay with distance. This formula implies an exponential decay of overpressure along a given radial and allows for different slopes in different directions. This approximate formula applies to all guns studied thus far. Figures 21 and 22 show the approximate decay of pressure and the angular dependence of α and A.

The range of α in the near field for the experiments, from Figure 22, is 1.32 to 1.52. Various investigators have presented values in the range of 1.02 to 1.44 for various explosive phenomena in the pressure range of interest. For very intense blast waves, for example near the surface of a high-explosive charge or near a nuclear explosion, the wave motion is highly nonlinear; and the decay is very rapid with distance. In this extreme the exponent may be as high as 3. In the other extreme of an infinitesimal amplitude wave traveling in an ideal gas, the exponent has the theoretical acoustic limit of 1. The present experimental results lie between these limits. As the wave propagates out to lower overpressures, say beyond 1 psi, the exponent should decrease with distance to the lower range of 1.0 to 1.1. The actual value is difficult to determine experimentally because atmospheric refraction has a pronounced effect on the intensity observed at distant points. Elaborate experiments have been conducted to determine the limit, and the results remain controversial. The limit value of 1.1, which is based on theoretical calculations for a 1-kiloton (kt) nuclear explosion in Needham[6] has been incorporated into the ANSI standard.[7]

More accuracy than that available from the above formula was required for planning the structural test firings on *New Jersey*. More elaborate expressions were found for the curves, as shown in the Figures 9 through 17. The coefficients for each radial were then curve-fitted to further expressions in order to follow the angular dependence of the blast field. Again, high-order splines were used to model the data. The final result is the overpressure contour curve in Figure 23. These curves were used with excellent results in the design of 16-in. gun experiments conducted on *New Jersey*[2,3] and *Iowa*.[8] Contours of positive duration are shown in Figure 24. Contours of impulse are shown in Figure 25. The impulse is defined as the time integral of overpressure during the positive phase, and the units are psi-ms. The duration and impulse curves were hastily prepared and are not of the same quality as the overpressure contour.

The overpressure contour was updated after the structural test firings on *New Jersey*. The guns were fired at various trains and elevations. Therefore, the instruments were not on the radials used for the Dahlgren experiments. The experimental data points were "rotated" onto the nearest 15-deg multiple through a formula based on Taylor's series of multivariable calculus and partial derivatives of the analytic expression for Figure 23. This allowed the additional data points obtained aboard ship to be used to enlarge the database and improve the accuracy of the blast pressure contour drawing. The rotated data points measured aboard ship are scattered about at various distances in Figures 9 through 17. The data points measured at Dahlgren are clustered at specific distances. A summary of the 16-in.

gunblast efforts as relate to shipbuilding and equipment for the Battleship Reactivation Program is documented in the *Naval Engineer's Journal*.[9]

FAR PROPAGATION OF 16-IN. GUNBLAST

The far propagation of 16-in. gunblast was initially studied during experiments in 1984, conducted in Dahlgren and Puerto Rico.[10] The study covered ranges from 10 to 36 nmi.

Interest in 16-in. gunblast propagation into the far field was renewed in 1987 in connection with research on the propagation of blast from accidental explosions of underground munitions storage facilities. This report is an outgrowth of a paper on 16-in. gunblast[11] invited to the Air Blast Exiting from Tubes Workshop sponsored by the Department of Defense Explosives Safety Board and the Norwegian Defense Construction Service. The purpose of the meeting was to share data and improve understanding of the flow from tunnel explosions.

The experiments of Yagla and Soo Hoo,[12] Soo Hoo and Moore,[1] and Pater,[13,14] show that most guns are reasonable models of one another. Their blast fields scale as their linear dimensions. The blast emerging from the mouth of a tunnel, say 10 ft in diameter, may be geometrically similar to the blast from a 16-in. gun, with a scale factor of 7.5 on all linear dimensions of the flow.

The far propagation is strongly dependent on atmospheric conditions. The experiments in NSWC TR 86-191[10] used data measured at ranges of 10 to 36 nmi in the vicinity of Dahlgren, Virginia, to make predictions for noise in the vicinity of Vieques, Puerto Rico, as a result of battleship gunnery exercises and qualification firings. The formula for the sound pressure level that resulted from the Dahlgren firings was

$$SPL(dB) = 117.5 - 28.76 \log R + 7.15(1+\cos\theta) \quad (2)$$

Here R is the distance in nmi from the gun and θ is the azimuth measured from the gun axis. The last term is the directivity, which accounts for the variation of intensity with azimuth. The sound pressure level is defined by the formula

$$SPL(dB) = 20 \log \Delta p/p_r \quad (3)$$

where the reference pressure, p_r, is 2.9×10^{-9} psi. The formula shows that the overpressure at a 1-nmi distance along the trajectory is 131.8 dB. Atmospheric refraction can alter the predicted sound pressure level by as much as 20 dB. The formula is for a "mean expected value" in that it was obtained by averaging a large body of data. However, the last term, the directivity, has no free constants and was assumed based on the work of Pater.[13]

The data from References 9 and 10 were analyzed by Reed.[15] He found that a directivity of the form $b(1+\cos\theta)^{1/2}$ would provide a slightly better fit to the data.

Greater precision is needed for the analysis of data from underground storage facilities and the determination of safe distance criteria. The above formula was developed for data in the range of 10 to 36 nmi. Blast is important in the design of underground munitions storage facilities so that safe distances for houses and other inhabited structures can be determined. The region of interest for underground tunnel explosions is in an intermediate range of distances between the near field, which was studied out to 2 psi, as originally done for the design of battleship equipment installations and the far field as discussed above. A third set of experiments was authorized by the Department of Defense Explosives Safety Board to fill in the data for the "intermediate" field. The board also requested a study of the decay exponent so that other tunnel explosion data could be correlated.

The data for the near field, intermediate field, and far field for azimuths of 30, 45, 60, 75, and 90 deg are plotted in Figures 26 through 30. Substitution of equation 1 in equation 3 shows that coefficient of logR in equation (2) is 20 α. The coefficients are shown on each plot for each radial. The exponent, α , for the far field is plotted on Figure 22.

The laboratory is concerned about the noise levels propagated into the surrounding community. There are three main concerns. The first is for the hearing safety of people in the community. Secondly, the laboratory makes every effort to avoid property damage in the community. The third concern is to minimize annoyance and annoyance complaints. The threshold sound pressure level for a temporary hearing loss due to infrequent exposures to impulse noise has been taken as 140 dB. A value of 146 dB was cited[7] as being the threshold level at which claims for window damage begin. Claims for window damage become quite numerous at 148 dB. Annoyance depends on many subjective factors and cannot be readily quantified.

When the data from Figures 26 through 30 are replotted onto maps of the Dahlgren range and community, the data show that the expected sound pressure levels are below 140 dB, except in positions in front of the gun that have to be cleared of personnel before firing. Due to atmospheric refraction, the sound pressure level can be higher than the mean expected level, hence the scatter in the data for far propagation. The theoretical upper limit (cylindrical divergence) for intensification is 20 dB and is shown by the dashed lines on Figures 26 through 30.

The laboratory employs a meteorological data gathering system and digital computers to predict the noise levels in the surrounding community and does not fire when the predicted values are greater than 135 dB. The calculations include a 20-dB safety factor for intensification at all calculated focal points. This keeps the pressure levels much lower than the glass breakage threshold and minimizes noise complaints.

The pressure at the muzzle is required for correlation of blast data from tunnel explosions. The 16-in. gun muzzle pressure was measured with an instrument installed through the side of the barrel approximately 4.0 in. from the muzzle. The pressure traces showed a peak muzzle pressure of 7.4 ±1.1 kpsi, an exponential decay, and a positive duration of 10.3 ±2.0 ms. The projectile muzzle velocity and hence the flow velocity at emergence was 2485 ±13.1 ft/sec. Theoretical calculations with a Lagrange internal ballistics model showed at the exit a temperature of 1527 deg K, a pressure of 9531 psi, a muzzle velocity of 2506 ft/sec, and a ratio of specific heats of 1.25. A charge of 660 lb of propellant was used.

SUMMARY

The Battleship Reactivation Program has led to interest in the blast from 16-in. guns. Land-based experiments were conducted at NSWC to obtain data on the blast field. Scale drawings of blast waves were developed from the experimental data. The data were analyzed with various curve-fitting and statistical methods. The data were presented in terms of contours of overpressure, duration, and impulse. The far propagation of blast was measured in experiments at Dahlgren and Puerto Rico. The far propagation data were presented in terms of a formulae and plots. The data have been used with excellent accuracy to design many gunfiring experiments for equipment on *Iowa*-class battleships and were used to determine safe-firing arcs for the main battery. The data were also used for designing naval gun fire support qualification and training exercises.

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APPENDIX

FIGURES SUPPORTING 16-IN. GUNBLAST EXPERIMENTS

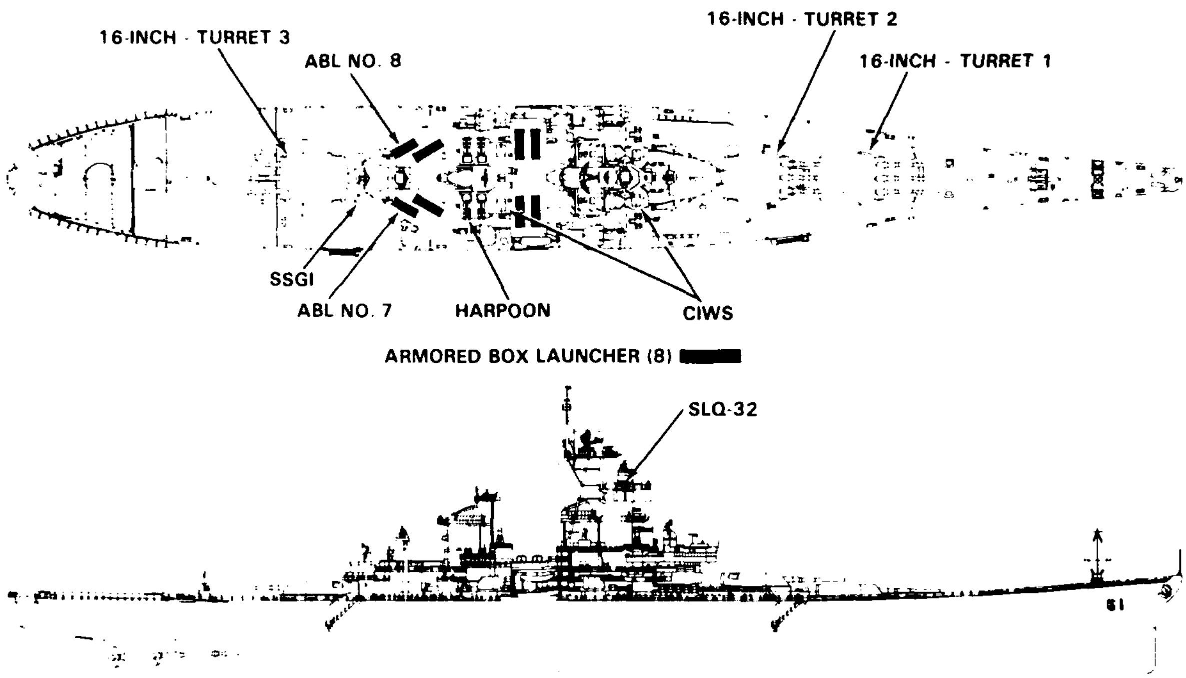


FIGURE 1. WEAPONS AND EQUIPMENT ON MODERNIZED U.S.S. *IOWA*- (BB 61) CLASS BATTLESHIPS

FIGURE 2. AERIAL PHOTOGRAPH OF *IOWA* FIRING ALL NINE 16-IN. GUNS (SHOCK WAVES ARE VISIBLE ON THE WATER)

FIGURE 3. DECK LEVEL VIEW FROM BOW OF *IOWA* FIRING 16-IN. GUNS

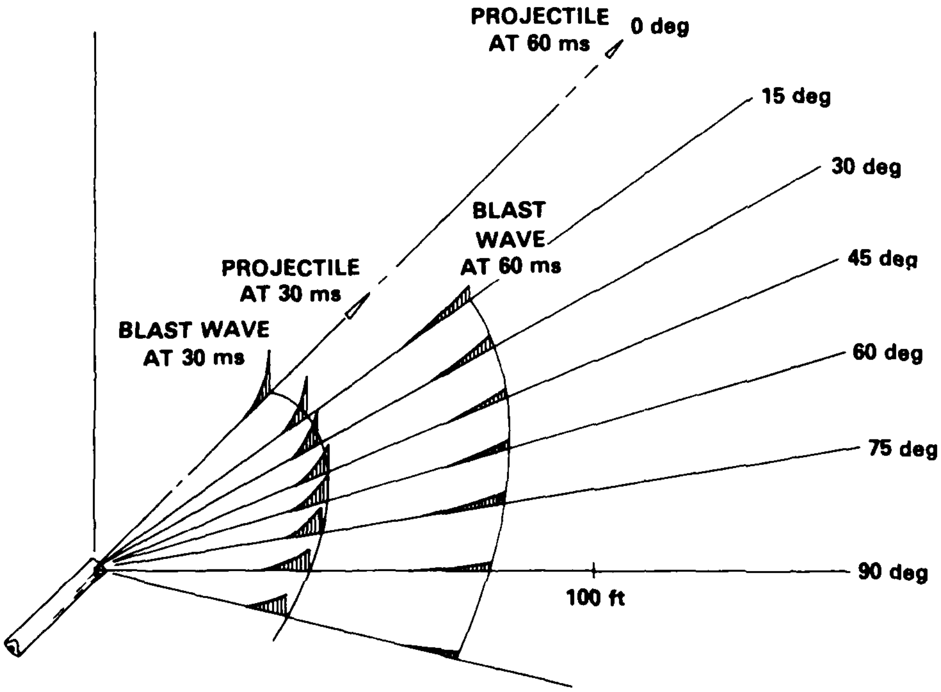


FIGURE 4. OBLIQUE PROJECTION OF BLAST WAVE AND PROJECTILE FROM 16-IN. GUN AT TWO TIMES (DRAWN TO SCALE FROM EXPERIMENTAL DATA)

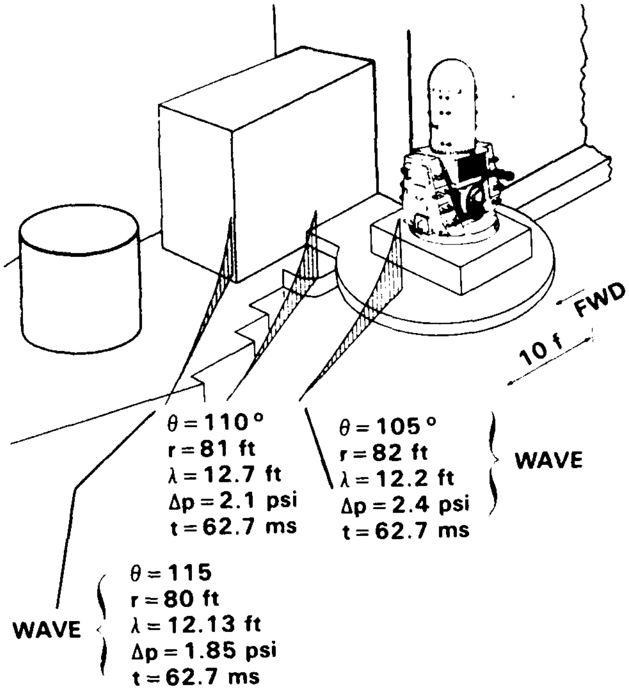


FIGURE 5. BLAST WAVE APPROACHING 05 LEVEL SPONSON AND CLOSE-IN WEAPON SYSTEM (CIWS) ON *IOWA*-CLASS BATTLESHIP (BASED ON DATA MEASURED AT DAHLGREN)

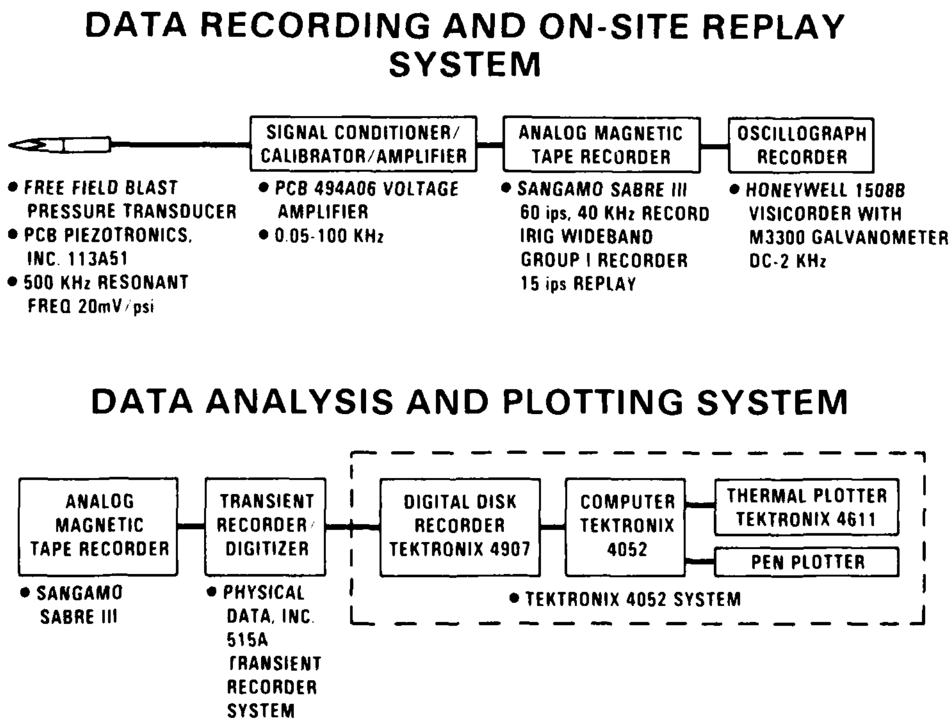


FIGURE 6. INSTRUMENTATION SYSTEM USED TO MEASURE 16-IN. GUNBLAST DATA

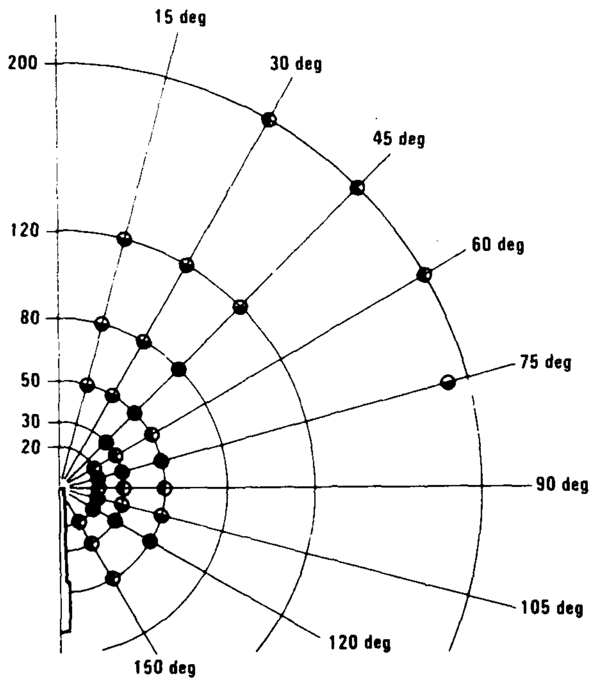


FIGURE 7. INSTRUMENT LOCATIONS FOR MEASUREMENT OF 16-IN. GUNBLAST DATA (DISTANCES ARE IN FEET)

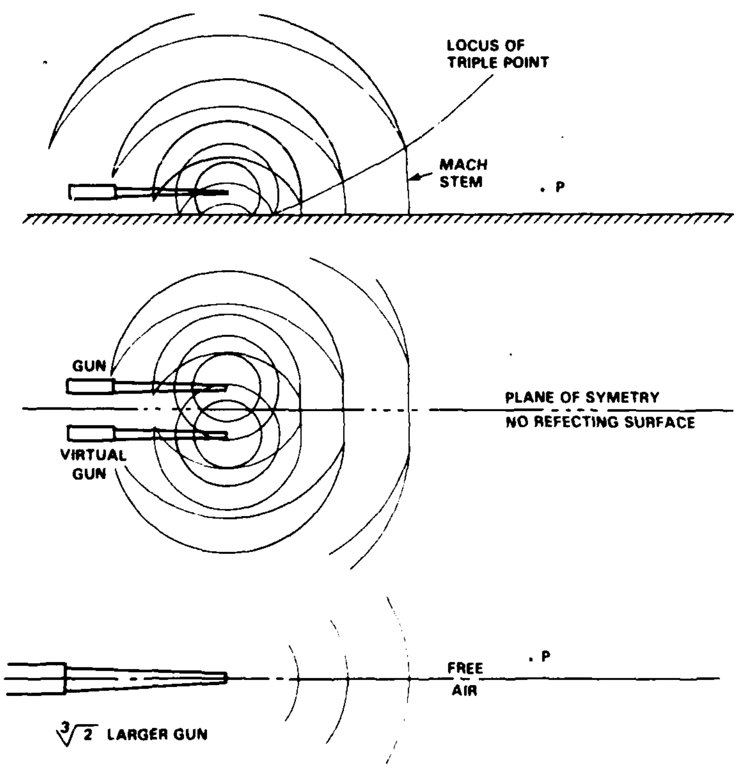


FIGURE 8. GROUND REFLECTION PROBLEM IN MEASURING 16-IN. GUNBLAST WHEN FIRING OVER LAND

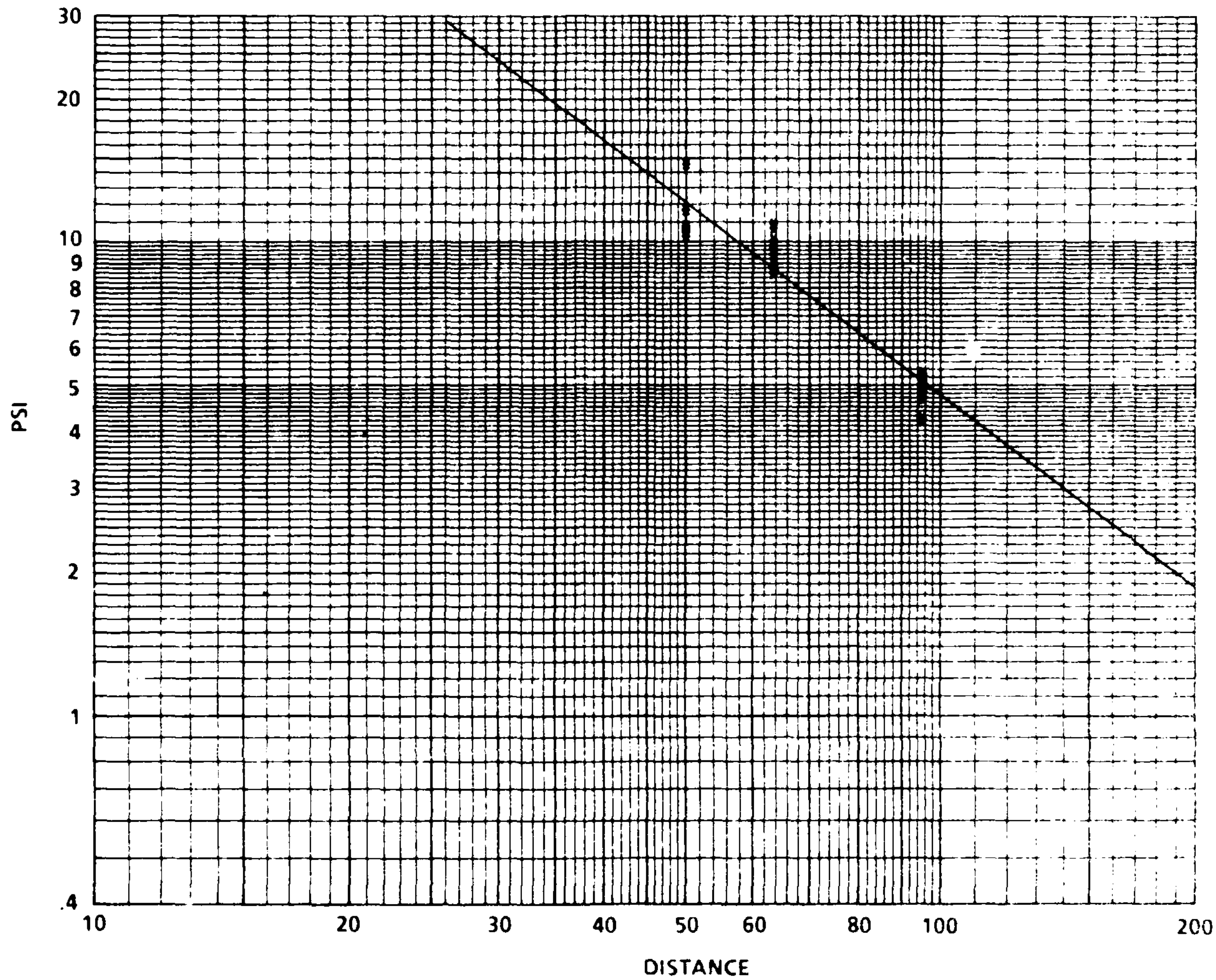


FIGURE 9 OVERPRESSURE VS DISTANCE ON 15 DEG RADIAL

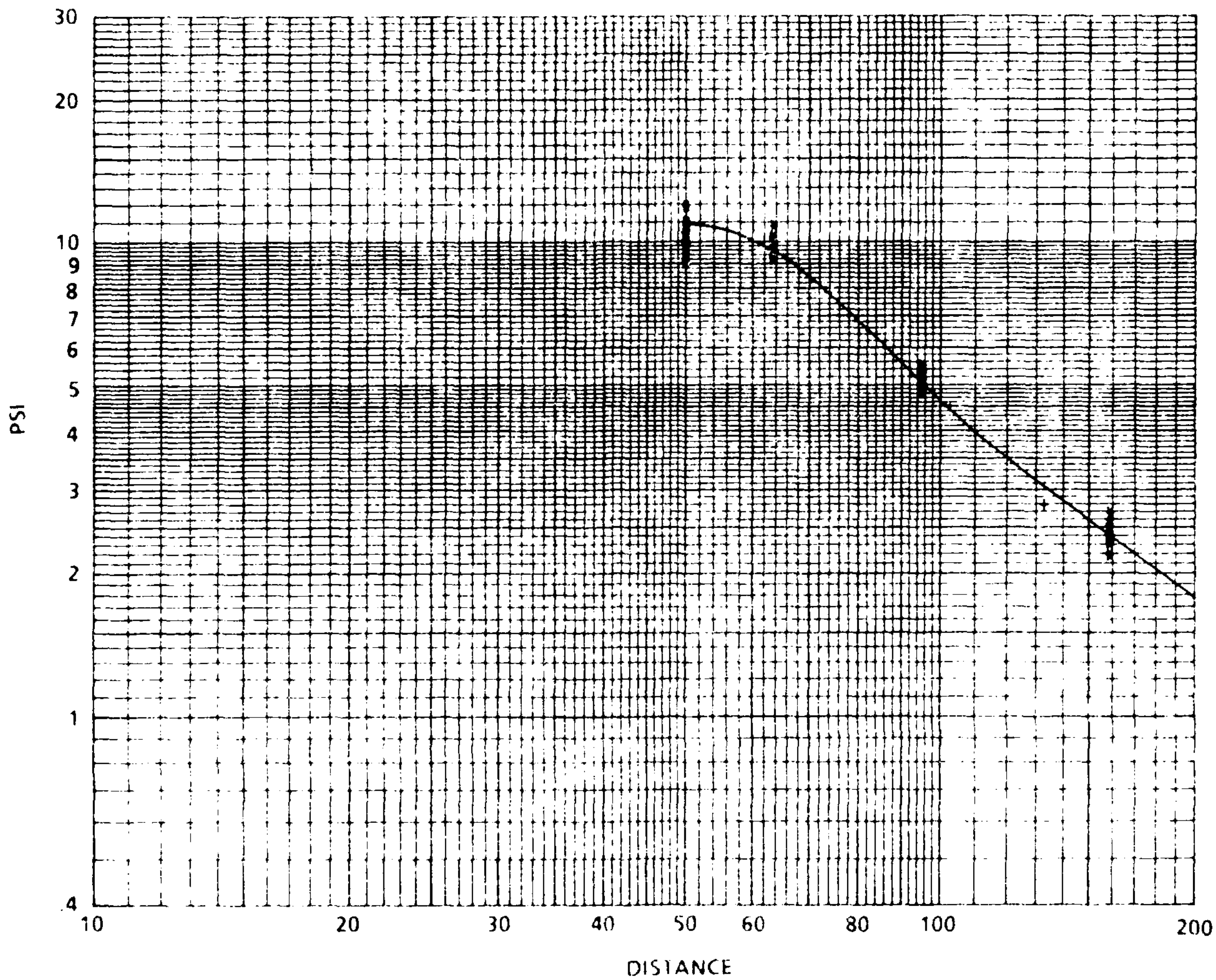


FIGURE 10. OVERPRESSURE VS DISTANCE ON 30 DEG RADIAL

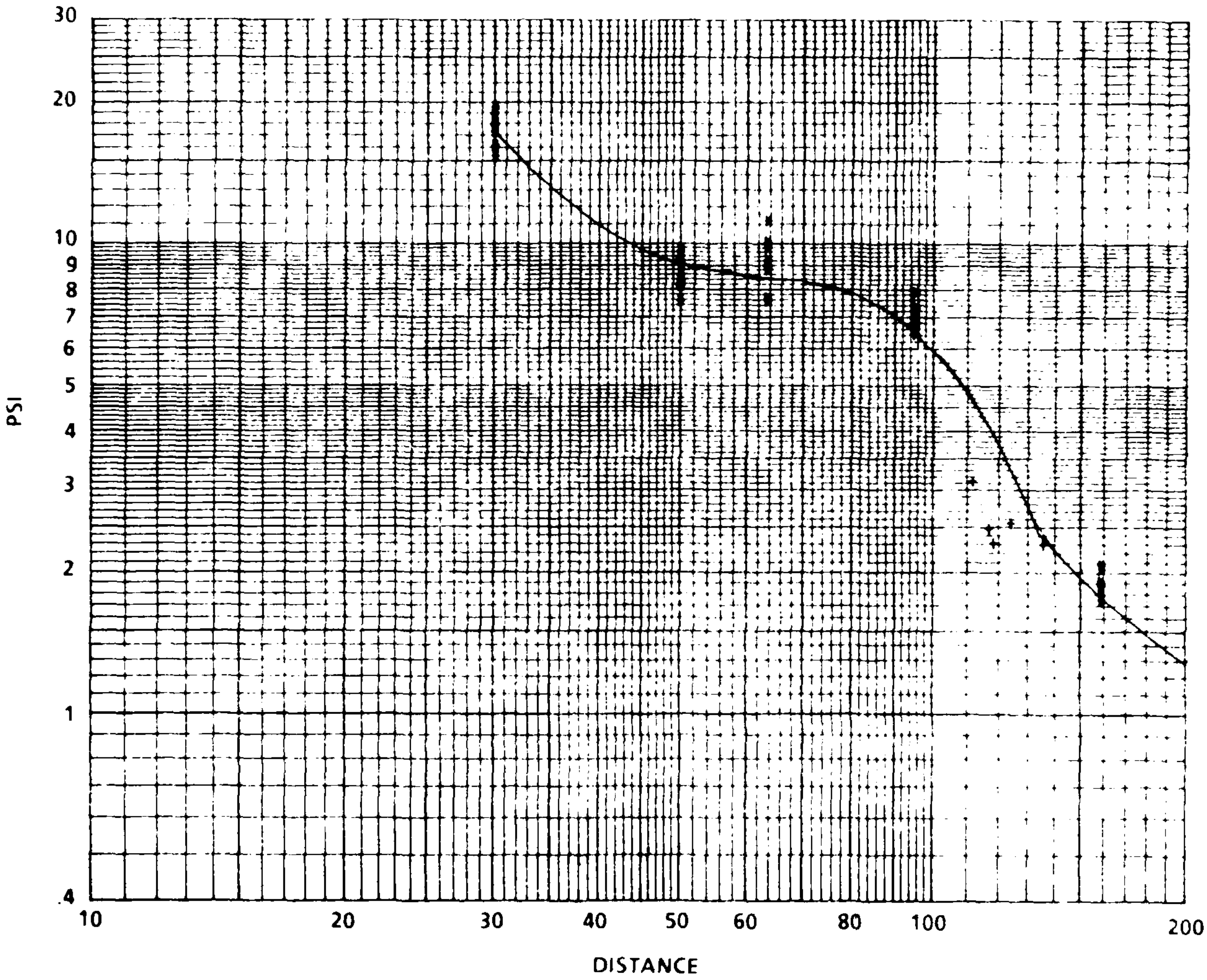
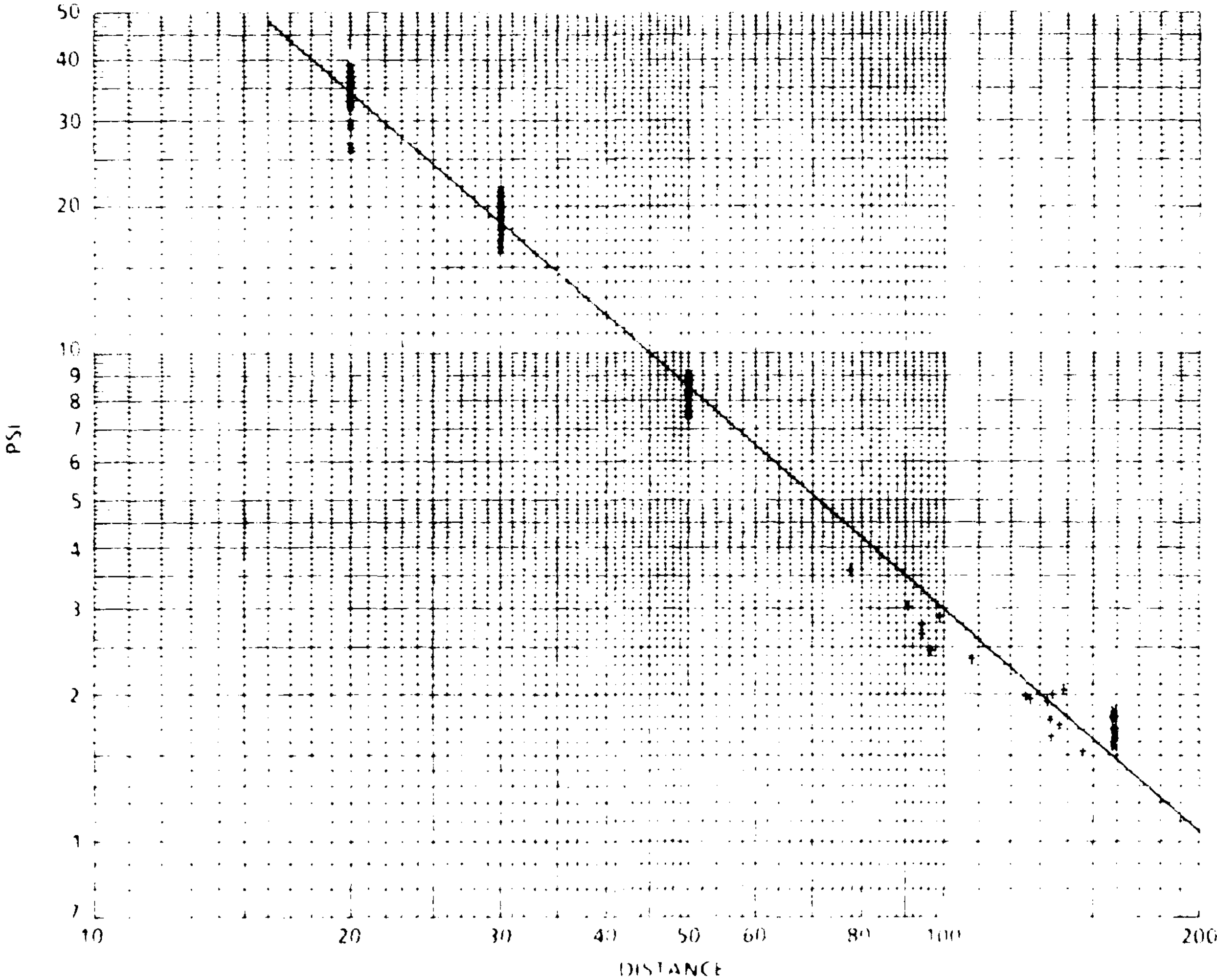


FIGURE 11 OVERPRESSURE VS. DISTANCE ON 45 DEG RADIAL



[illegible] OVERPRESSURE VS DISTANCE [illegible]

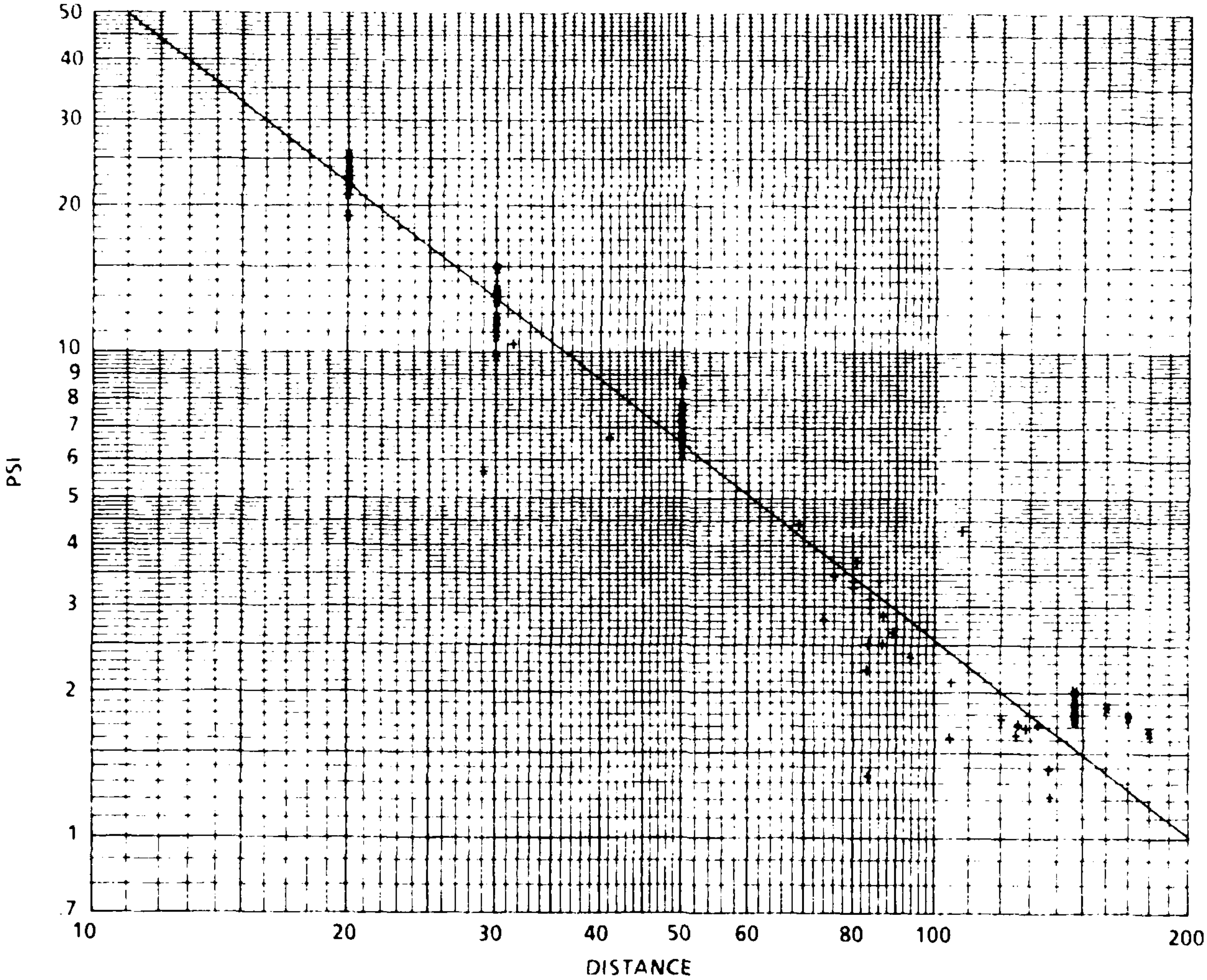


FIGURE 13 OVERPRESSURE VS DISTANCE ON 75 DEG RADIAL

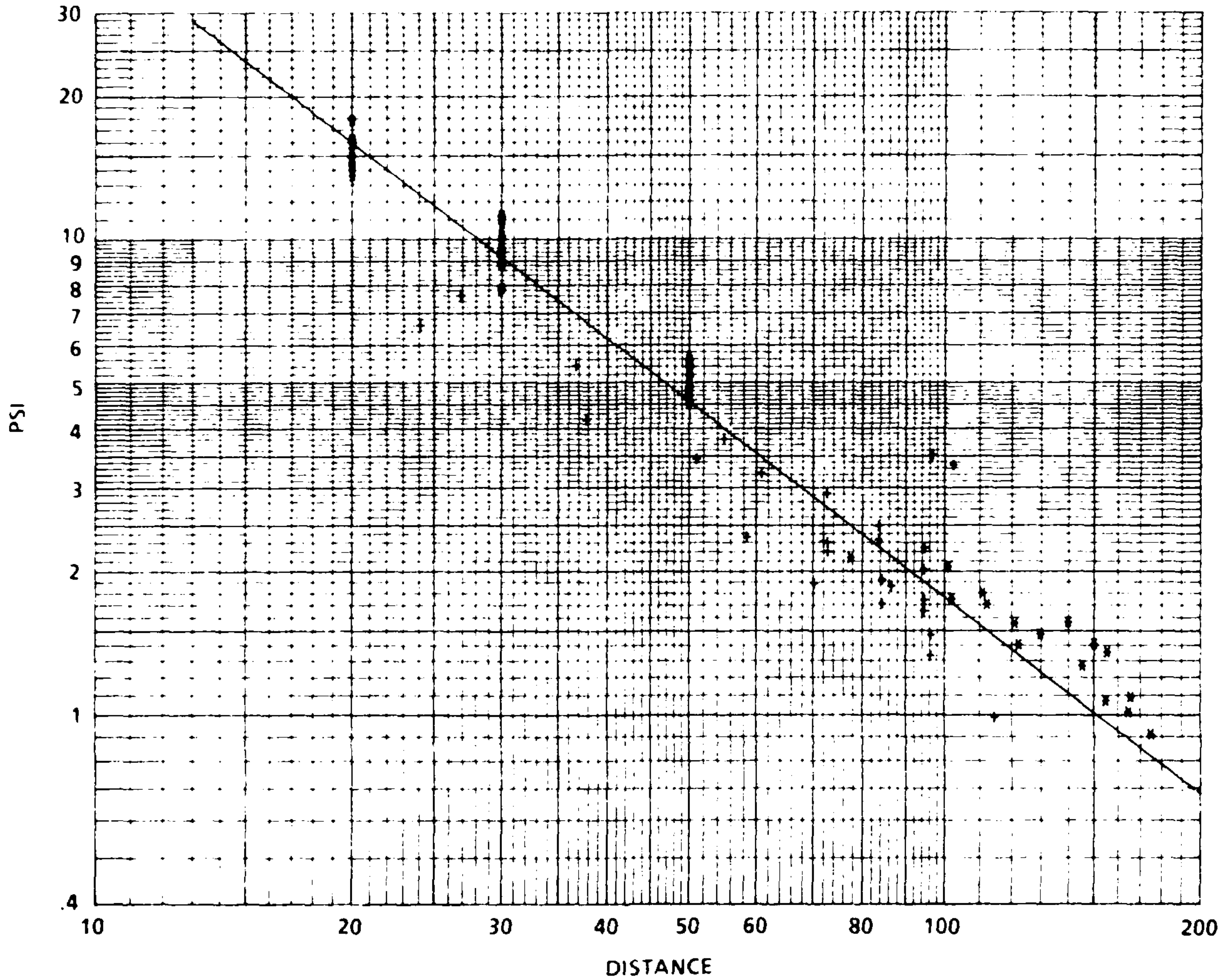


FIGURE 14 OVERPRESSURE VS DISTANCE ON 90 DEG RADIAL

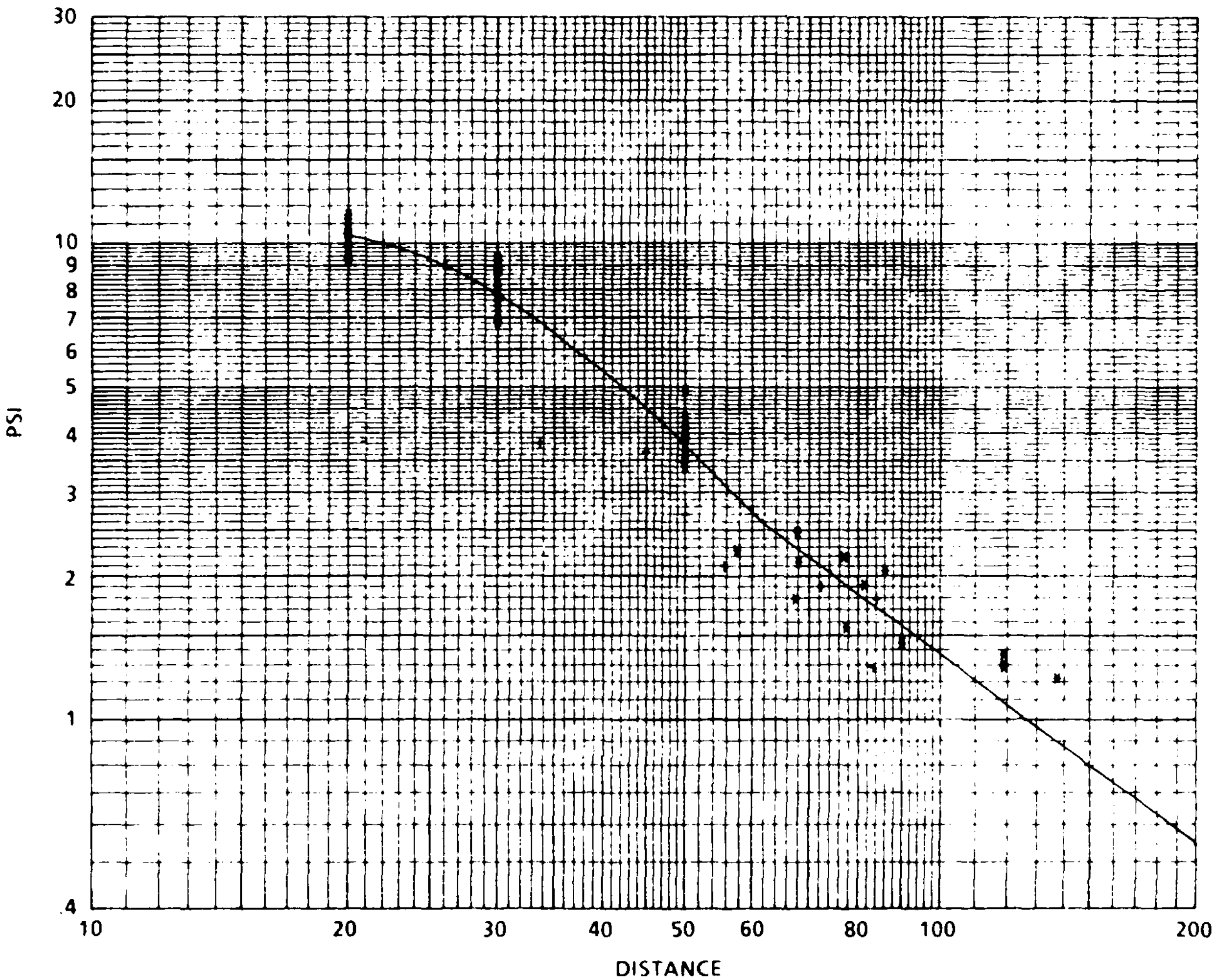


FIGURE 15. OVERPRESSURE VS. DISTANCE ON 105-DEG RADIAL

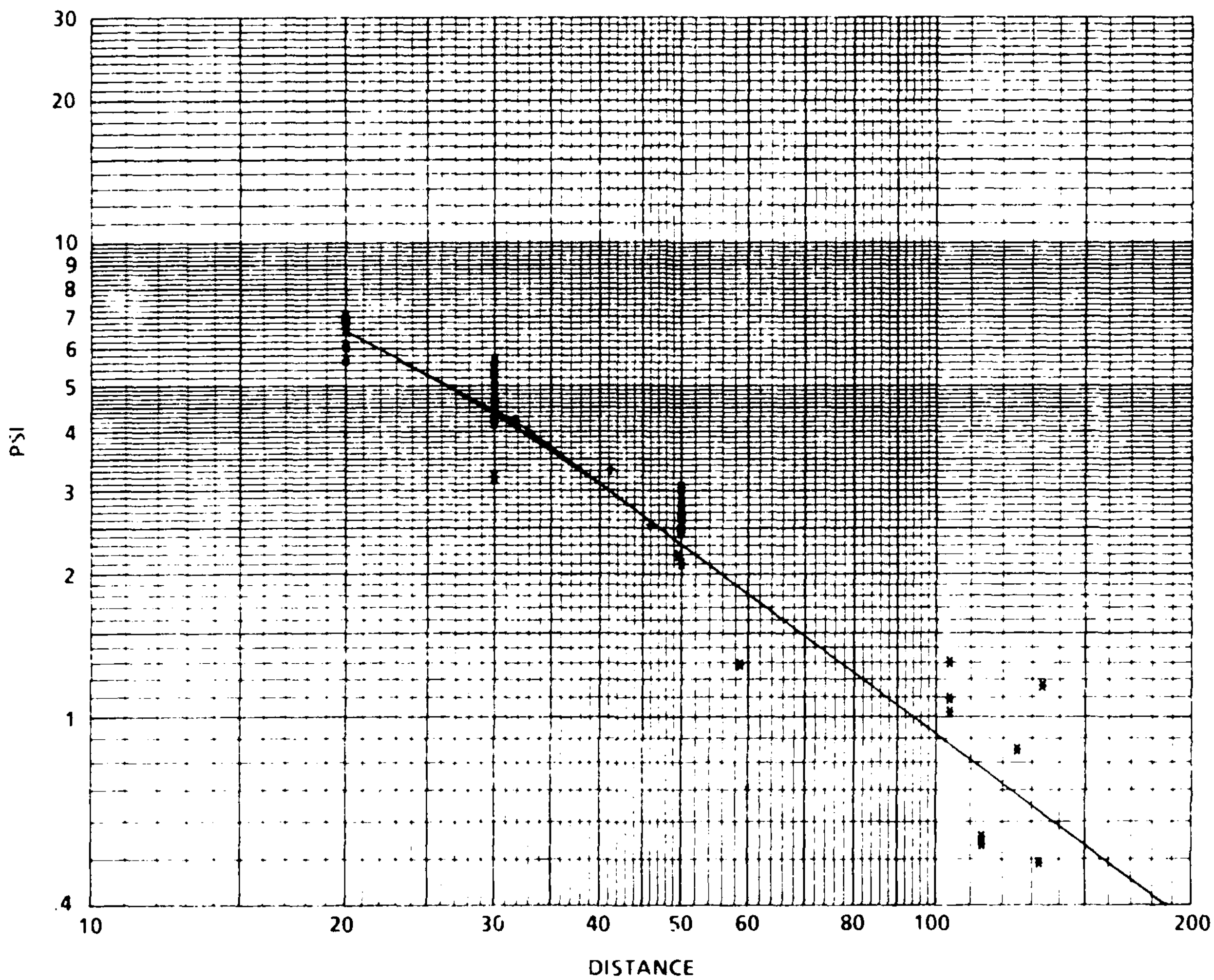


FIGURE 16. OVERPRESSURE VS. DISTANCE ON 120 DEG RADIAL

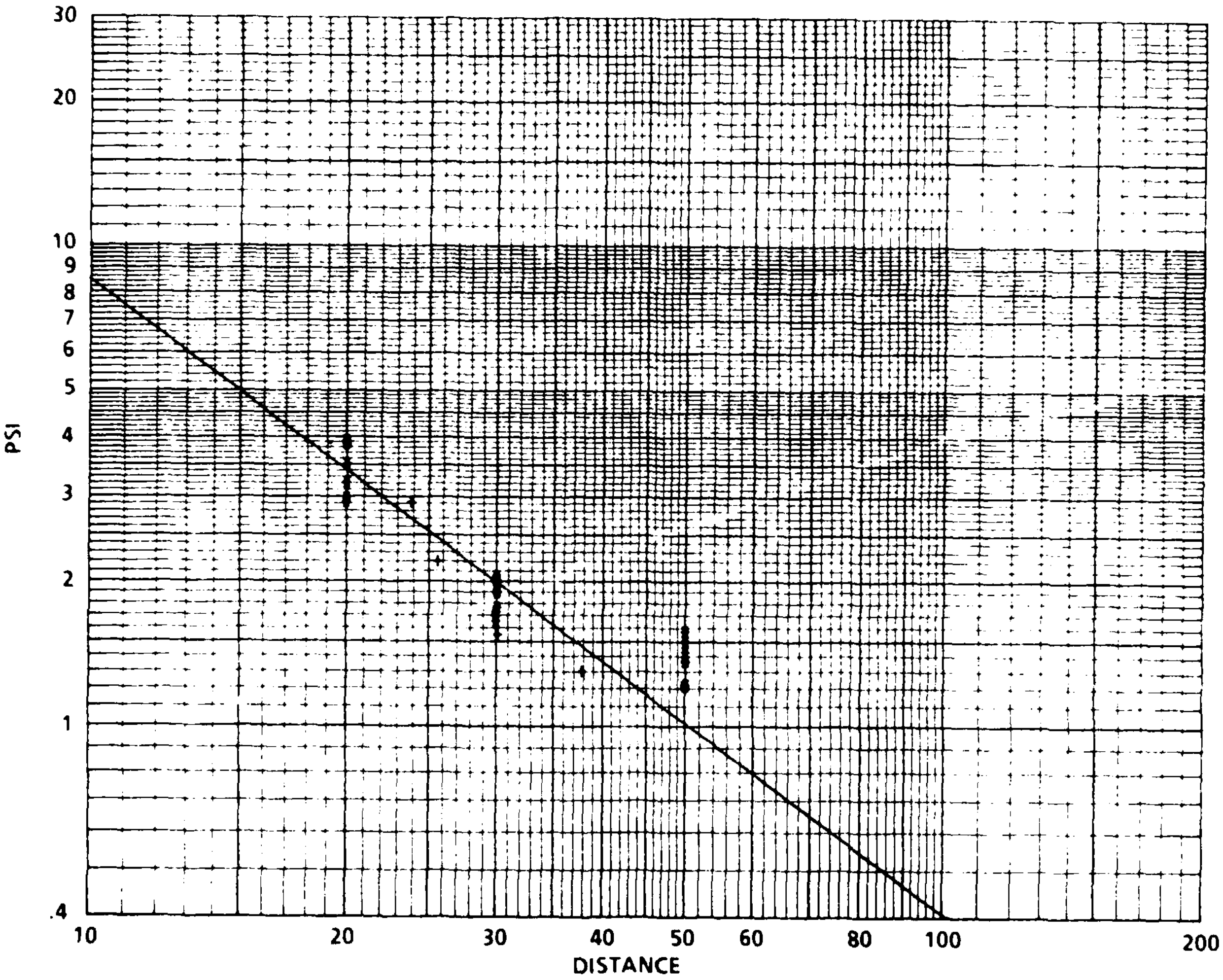


FIGURE 17. OVERPRESSURE VS. DISTANCE ON 150-DEG RADIAL

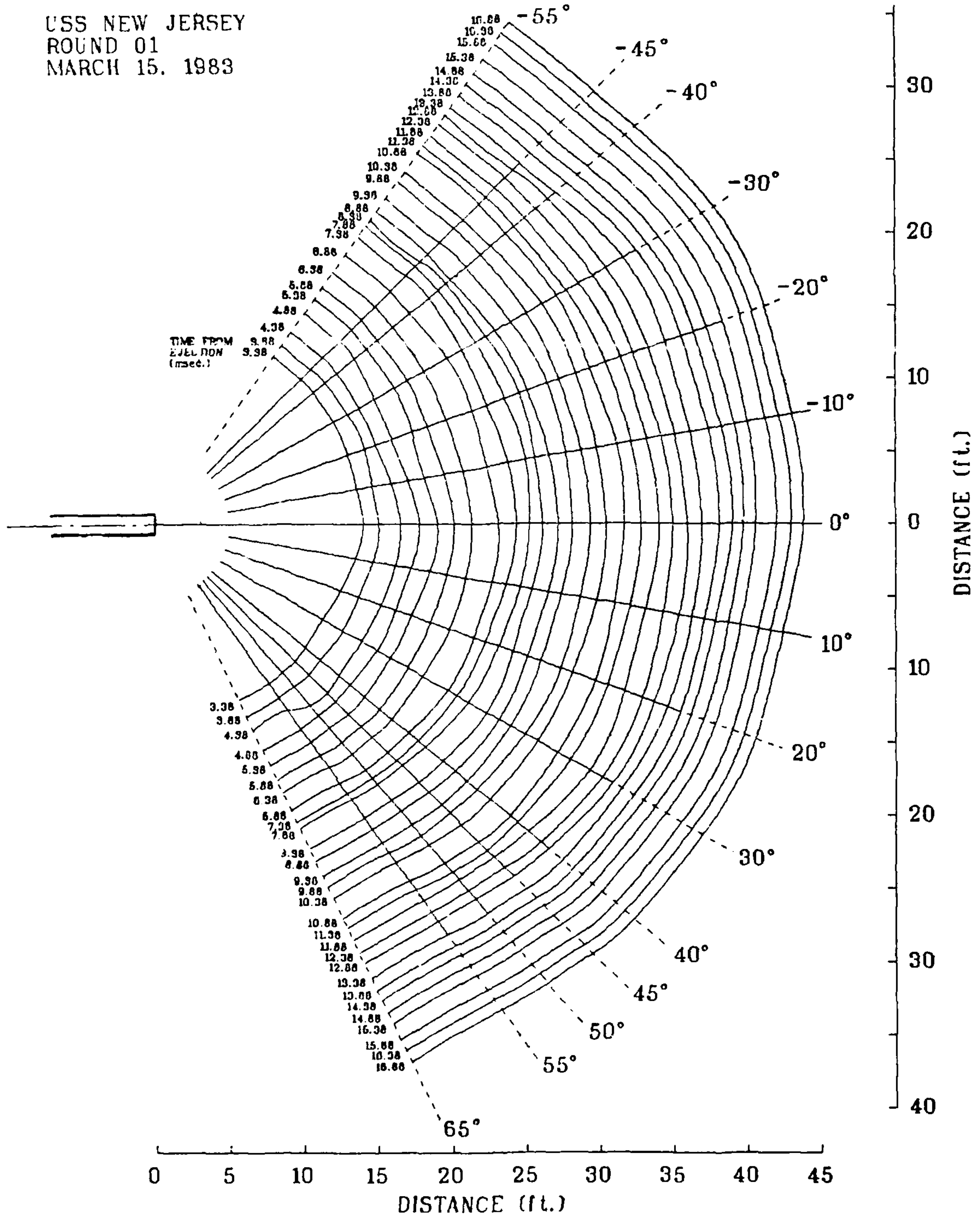


FIGURE 18. EXPERIMENTAL SHOCK WAVE PROPAGATION FROM A 16-IN. GUN

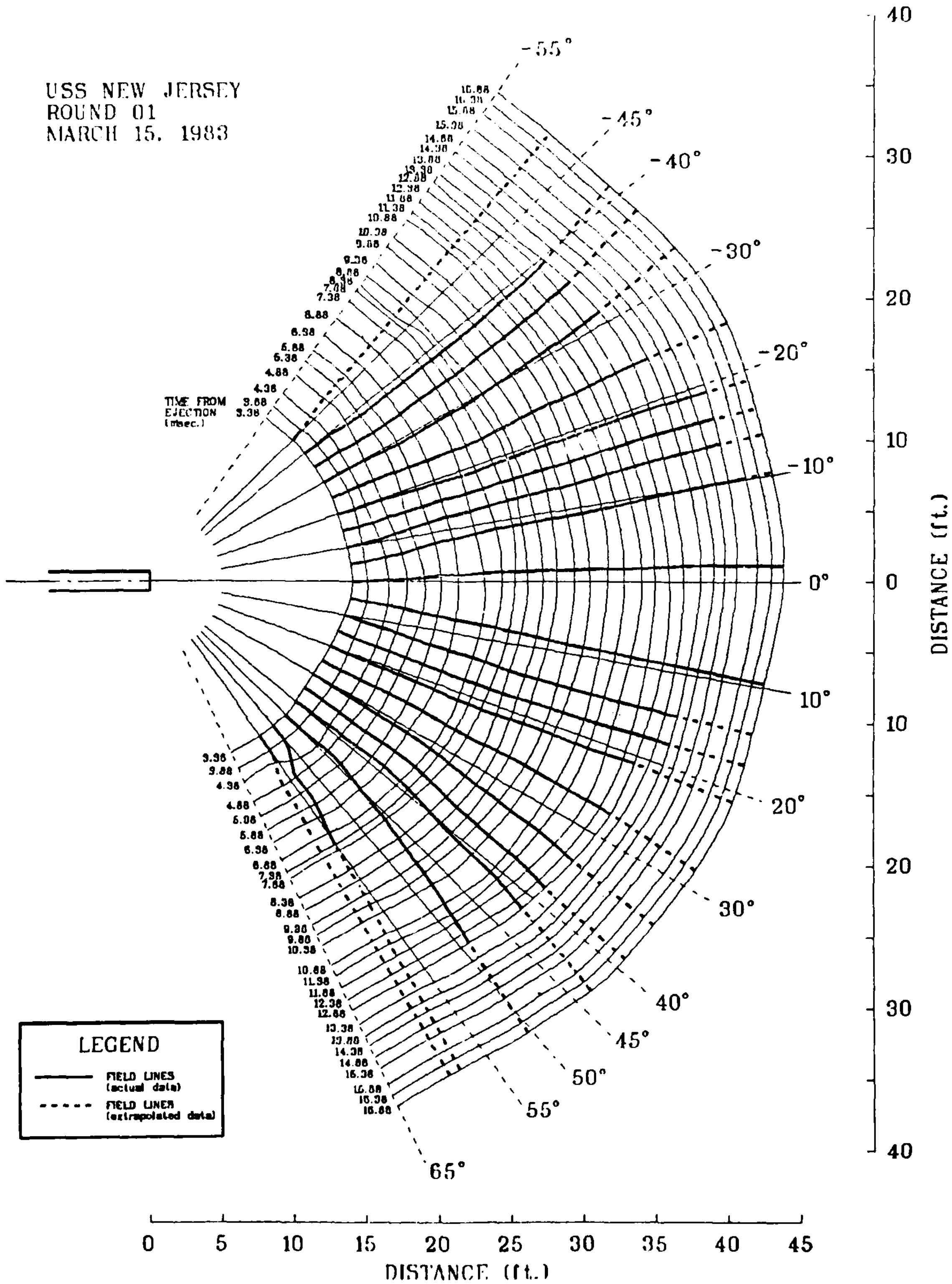


FIGURE 19. EXPERIMENTAL SHOCK WAVE PROPAGATION FROM A 16-IN. GUN SHOWING FIELD LINES

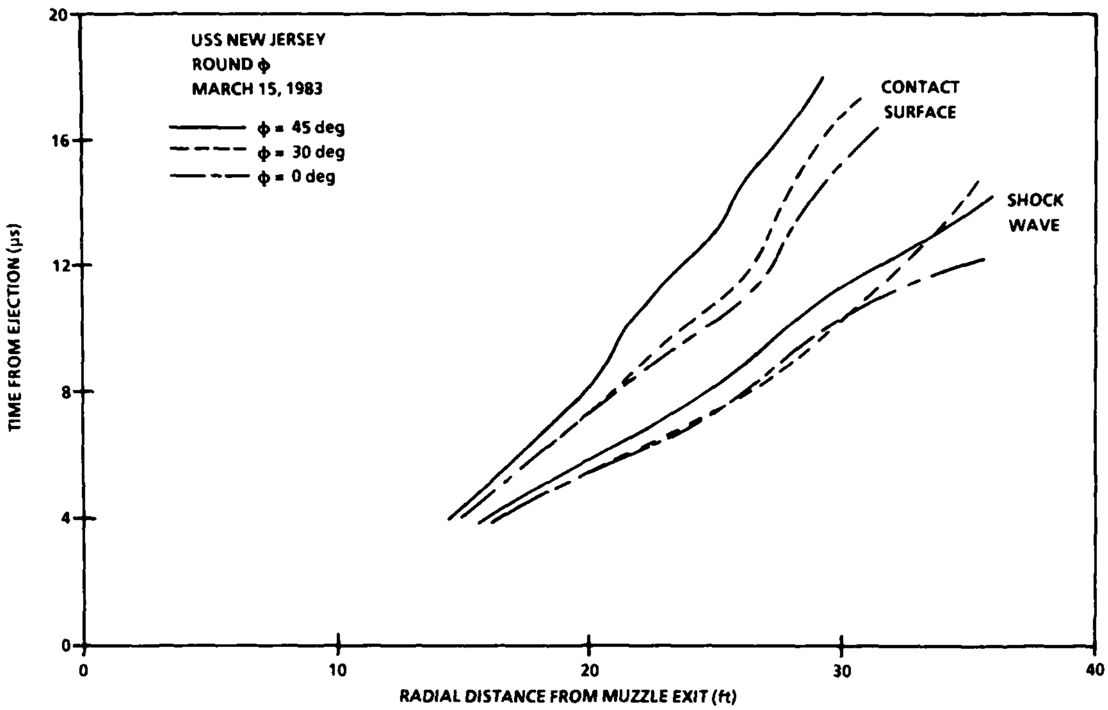


FIGURE 20. SHOCK WAVE AND CONTACT SURFACE TRAJECTORIES FOR 16-IN. GUN

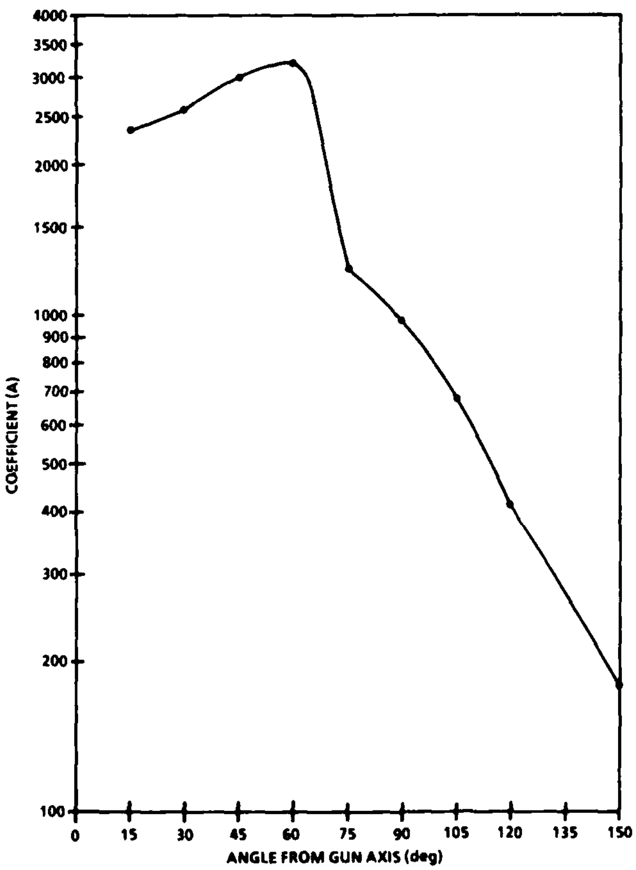


FIGURE 21. COEFFICIENT "A" DEPENDENCE ON ANGLE FROM TRAJECTORY

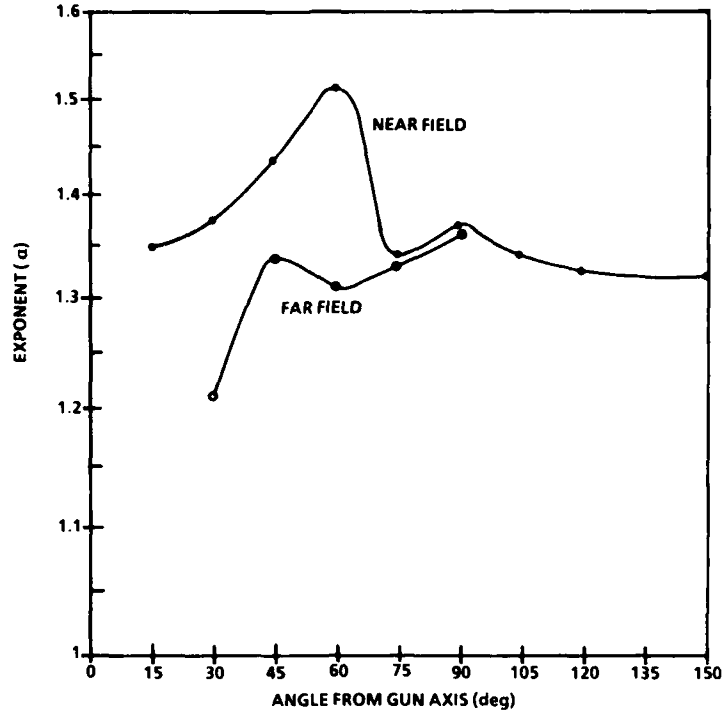


FIGURE 22. LOGARITHMIC DECAY EXPONENT, α, DEPENDENCE ON ANGLE FROM TRAJECTORY

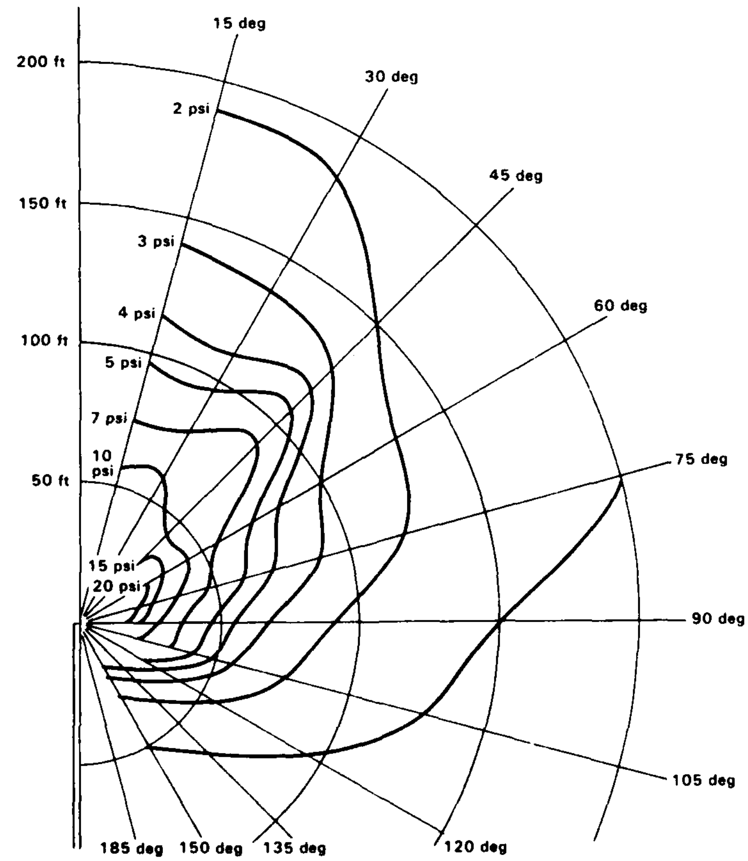


FIGURE 23. CONTOURS OF OVERPRESSURE FROM A 16-IN. GUN

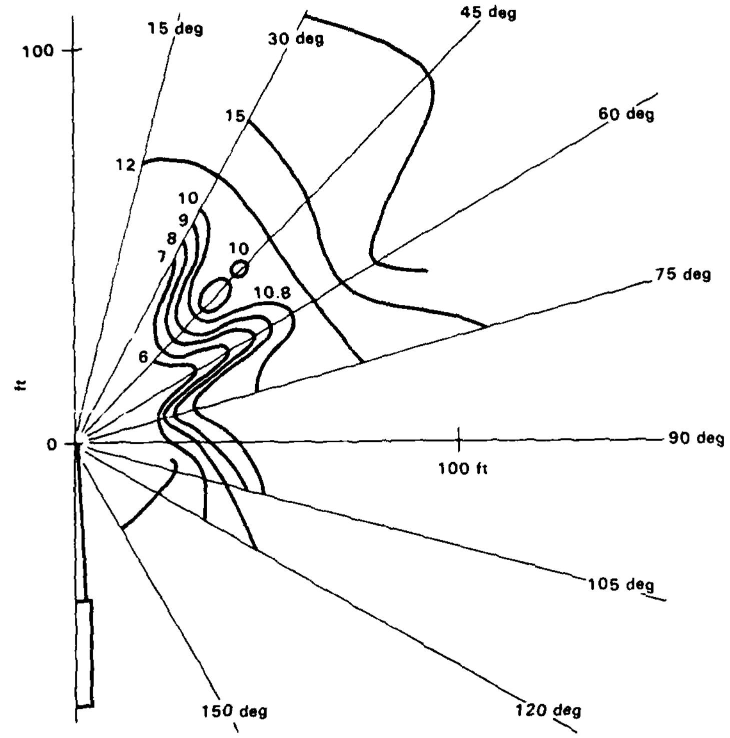


FIGURE 24. CONTOURS OF POSITIVE PHASE DURATION FROM A 16-IN. GUN

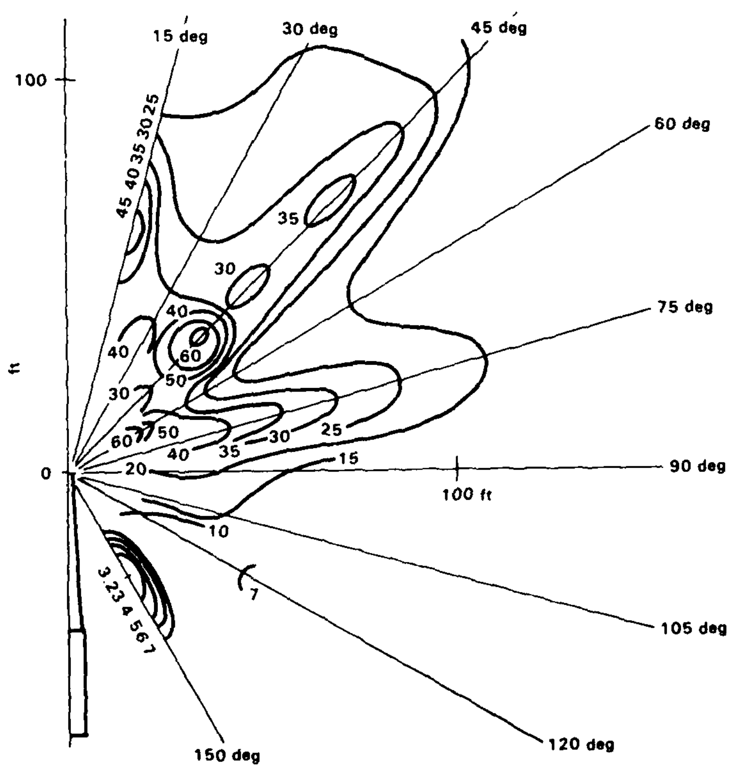


FIGURE 25. CONTOURS OF POSITIVE IMPULSE FROM A 16-IN. GUN

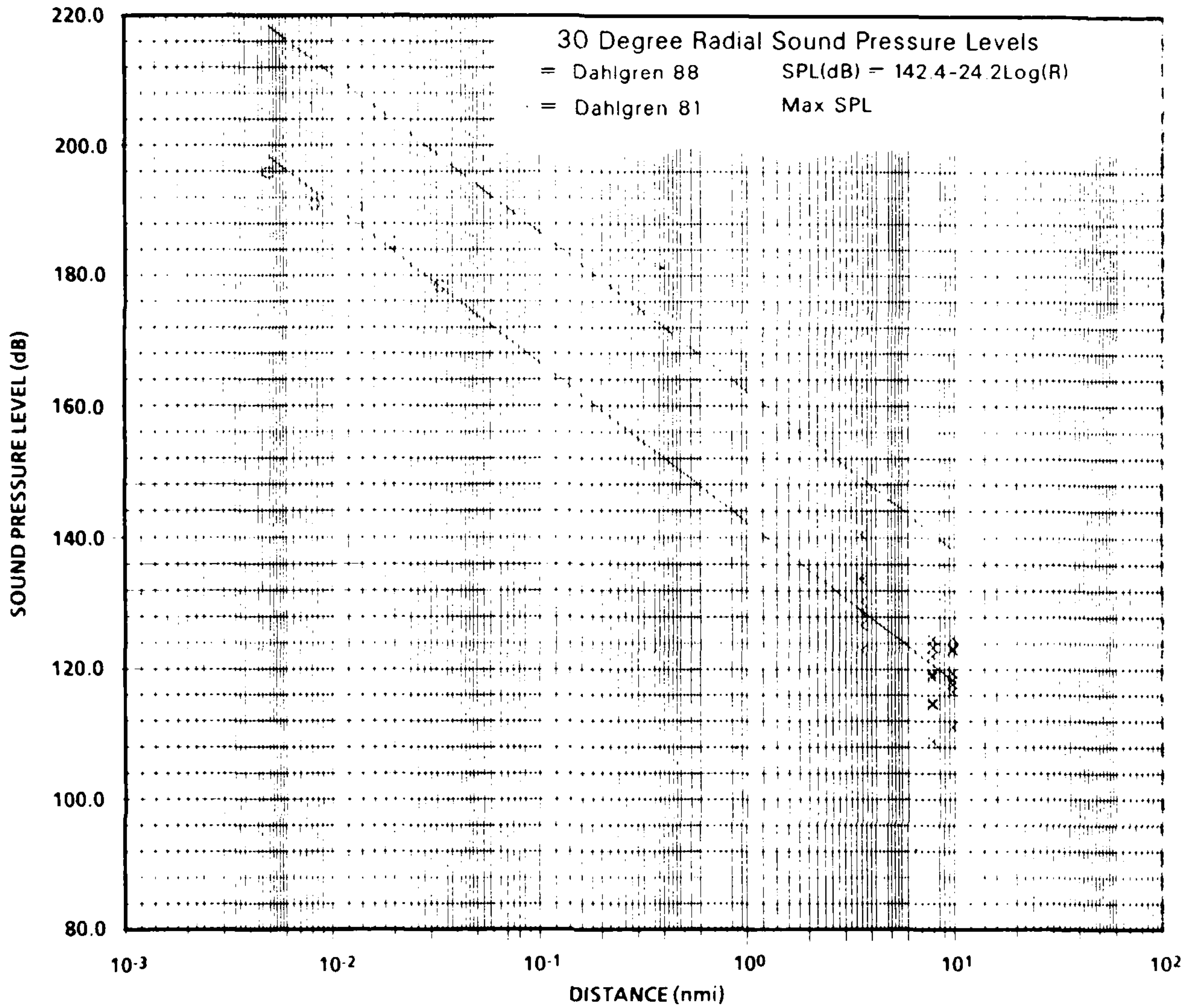


FIGURE 26. FAR PROPAGATION OF 16-IN GUNBLAST ALONG 30-DEG RADIAL

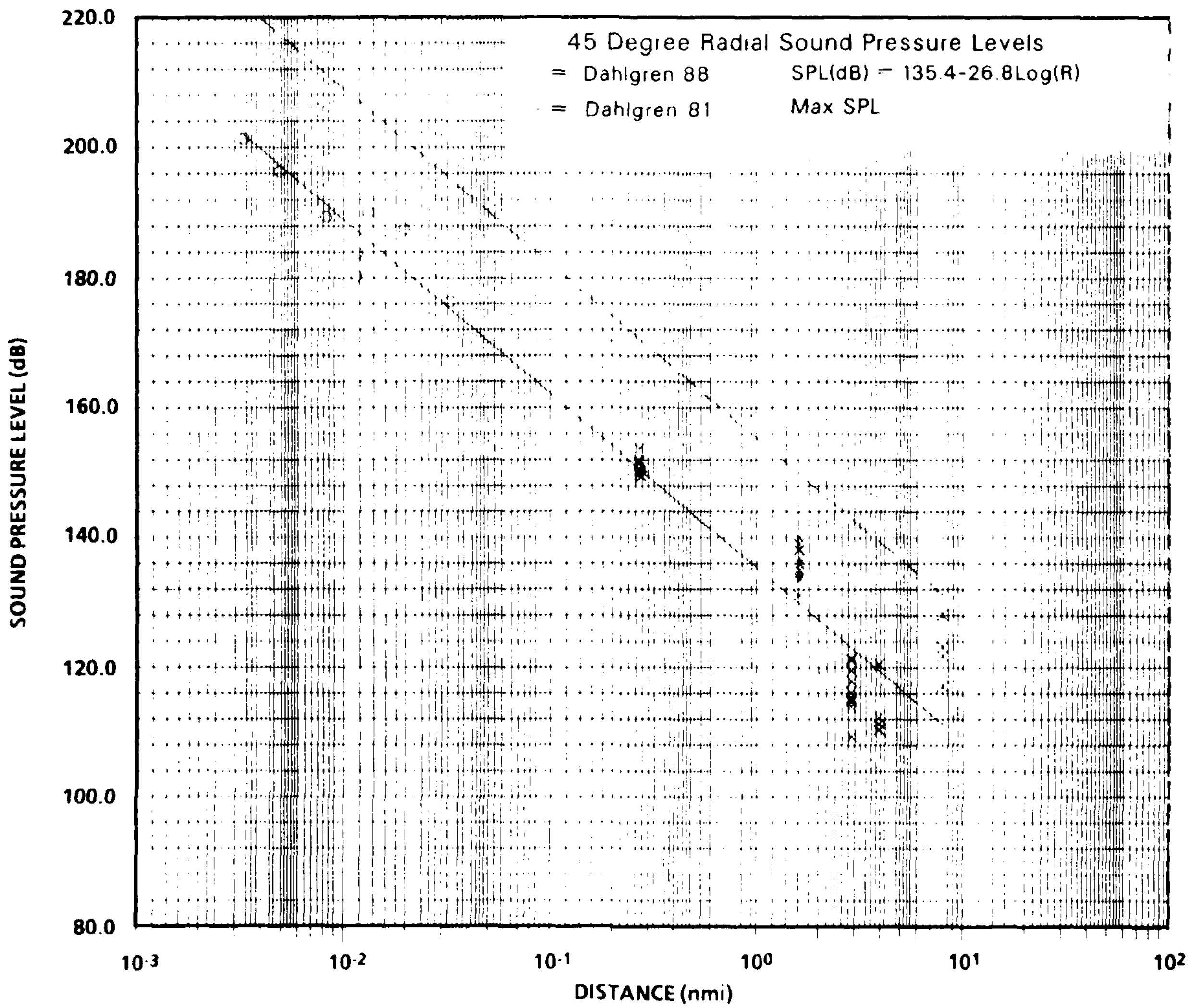


FIGURE 27. FAR PROPAGATION OF 16-IN GUNBLAST ALONG 45-DEG RADIAL

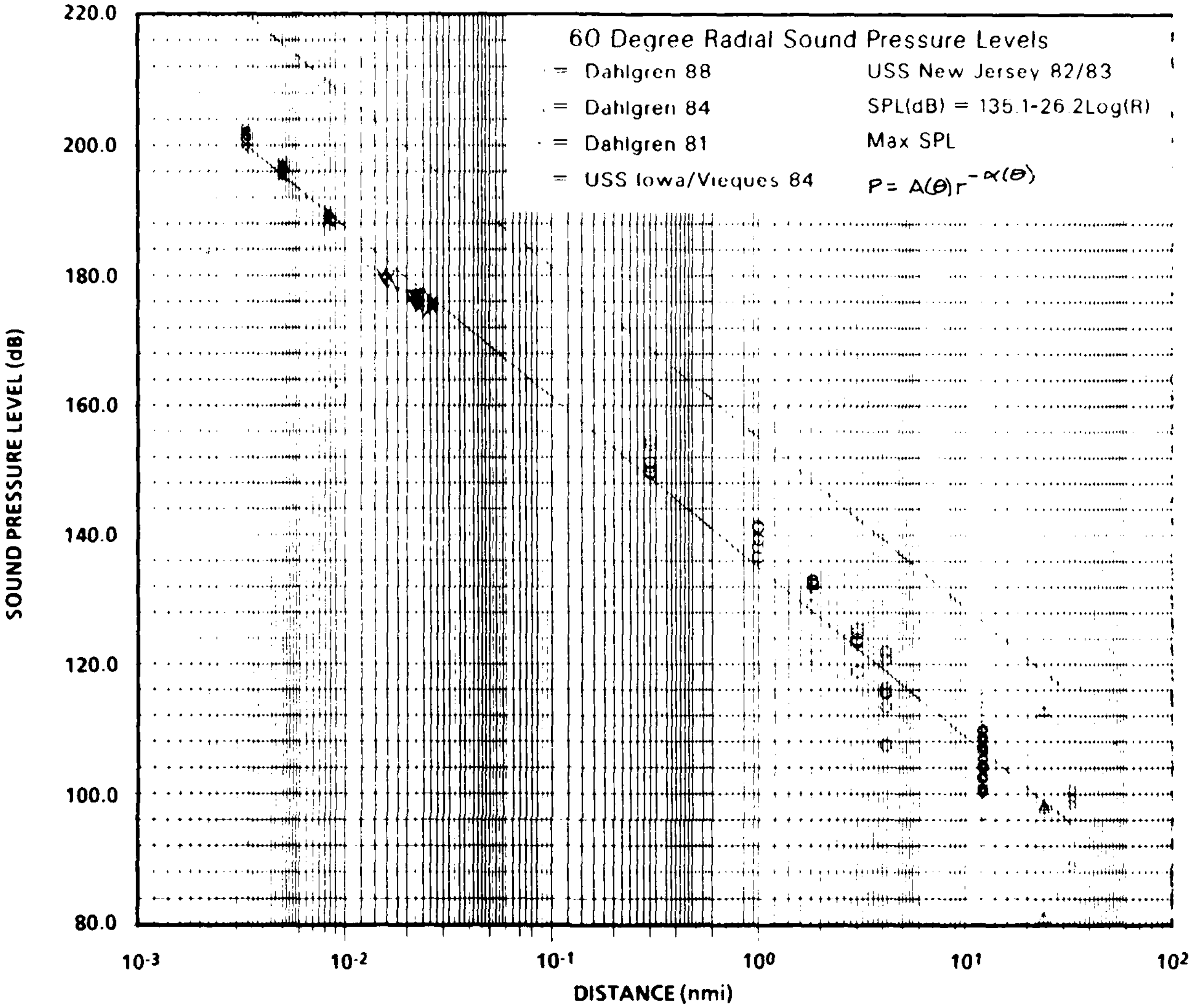


FIGURE 28. FAR PROPAGATION OF 16-IN GUNBLAST ALONG 60-DEG RADIAL

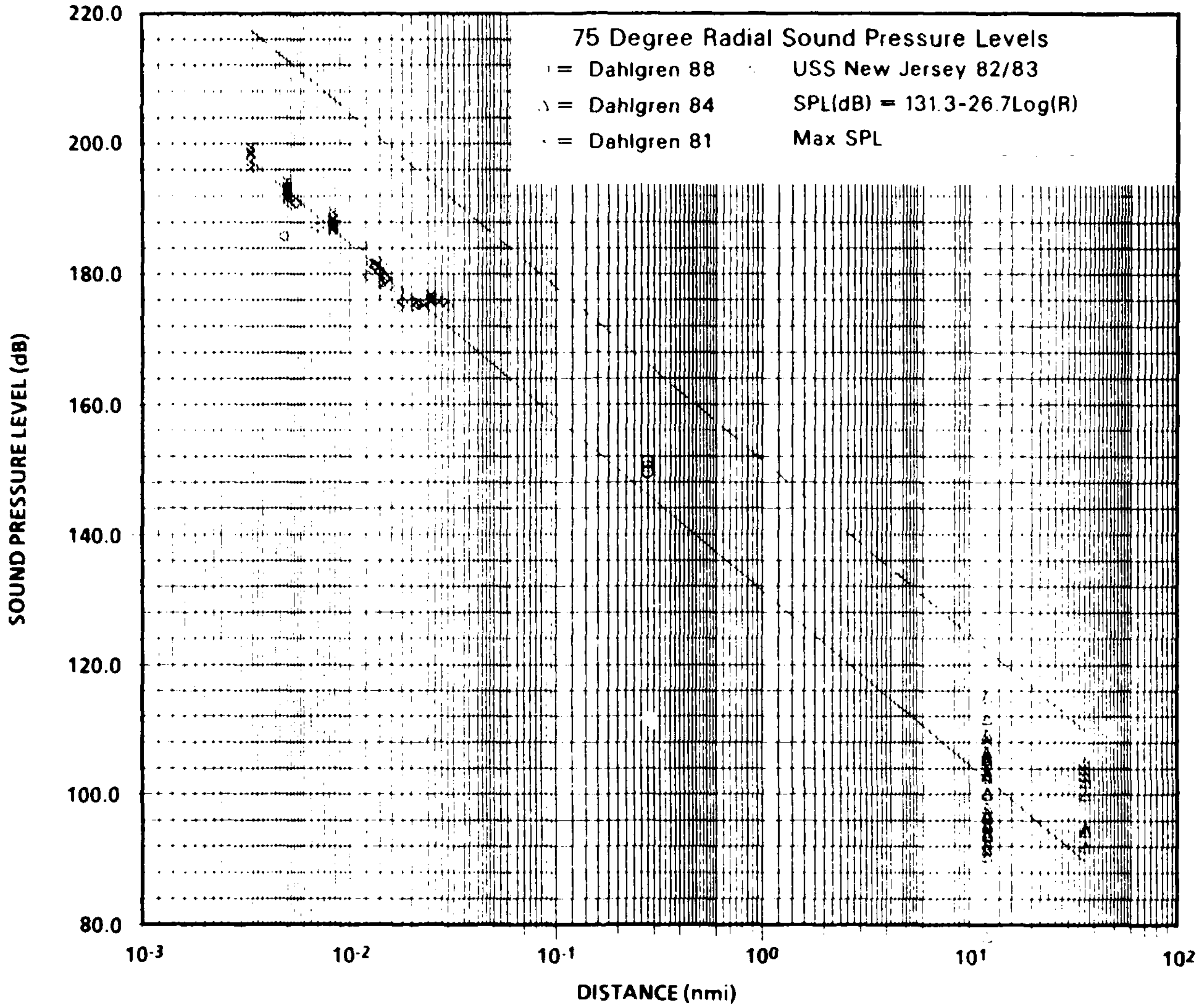


FIGURE 29. FAR PROPAGATION OF 16-IN GUNBLAST ALONG 75-DEG RADIAL

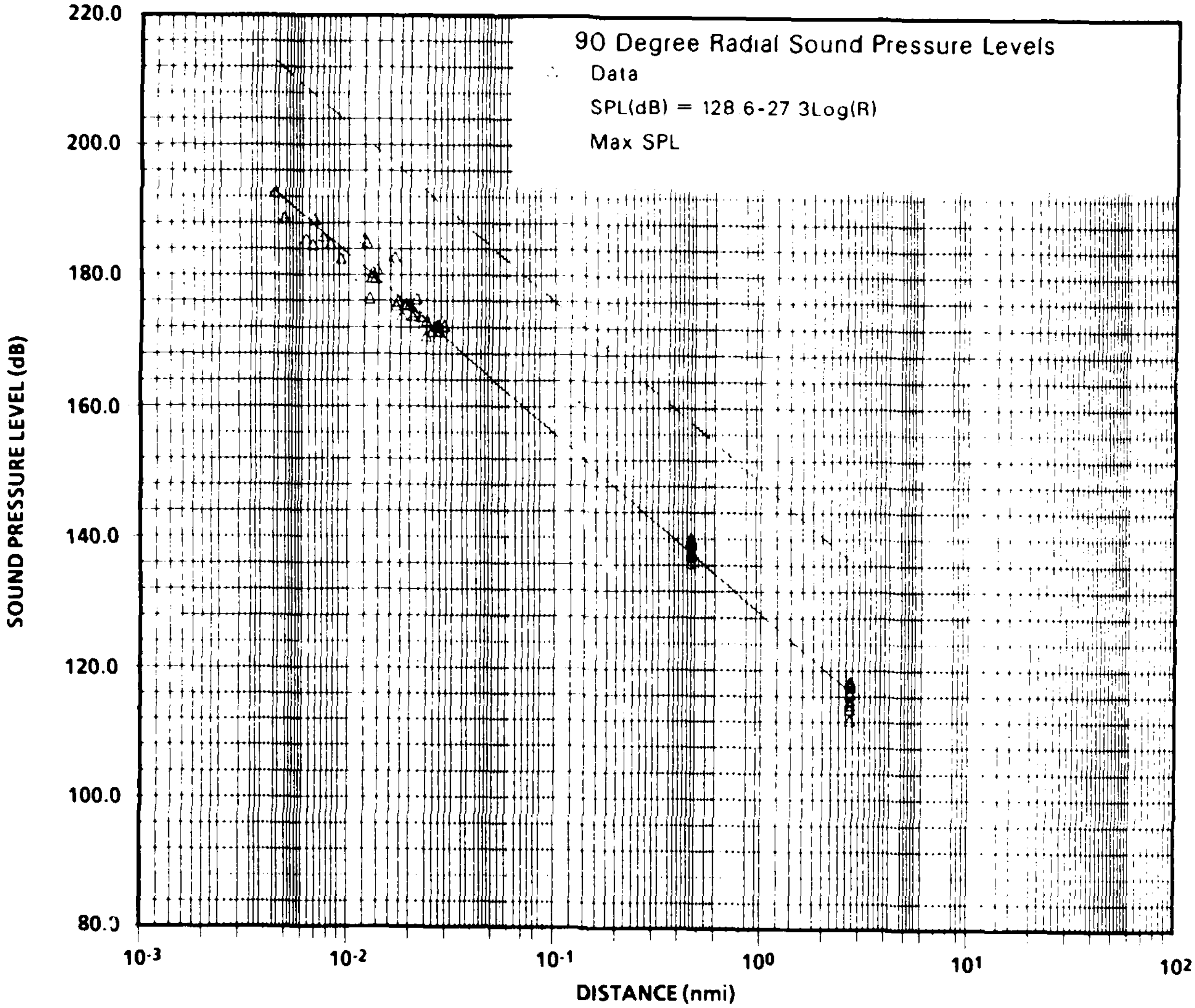


FIGURE 30. FAR PROPAGATION OF 16-IN GUNBLAST ALONG 90-DEG RADIAL

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