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CHARACTERISTICS OF THE SHOCK WAVE GENERATED IN AIR BY A BLASTING CAP

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The propagation of the shock wave generated in air by a very small surface explosion, a commercial No. 6 electric blasting cap, has been studied. A large number of time-resolved pressure histories were recorded with piezoelectric transducers at distances over the range of 3.05 to 80.8 meters from the explosion point. The observed range of peak air shock pressures was from ~~2×10^{-2}~~ bars down to ~~2×10^{-4}~~ bars. Comparisons with TNT surface burst data for much larger explosions show that the peak pressure-distance attenuation exponents are the same. Based on these pressure-distance data, the yield of the No. 6 electric blasting cap used is approximately 0.4 grams of TNT. Even at the lowest peak pressures measured, the wave shapes are characteristic of typical airblast shock waves. An essentially triangular positive pressure phase is followed by a negative pressure phase of much lower amplitude and longer duration; this is unlike the signatures of sonic booms which are highly symmetric. The effect of the asymmetry on the energy density spectrum of the blasting cap is also discussed. ( )

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AIR/GROUND EXPLOSIONS DIVISION
NAVAL ORDNANCE LABORATORY
Silver Spring, Maryland

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Characteristics of the Shock Wave Generated in Air by a Blasting Cap

This report represents the results of an experimental program undertaken to study the airblast characteristics of small explosion sources. The effort reported herein illustrates the usefulness of small explosions for conducting scaled experiments to study blast propagation and response.

This work was part of an effort conducted under AIRTASK A05-510-078/292-1/W36560, Work Unit PMA-51-1.

The use of company names in this report is for technical information purposes only. Neither endorsement nor criticism is intended.

GEORGE G. BALL
Captain, USN
Commander

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INTRODUCTION

A very large volume of airblast data has been amassed from chemical and nuclear explosions during this past quarter century. The applications for these explosion studies were primarily of a military damage nature and the shock overpressures were in the range of approximately 0.1 bars and higher. More recent measurements have been extended down to approximately 3 x 10^{-3} bars for explosion yields in the range of 4.5 to 91 metric tons of TNT. The study described in this paper presents the results of recent measurements on very small explosions in air, extending the measured shock pressure range down to 2 x 10^{-4} bars.

EXPERIMENTAL TECHNIQUES AND DATA

The explosion source used throughout this study was a commercial No. 6 electric blasting cap[1]. The blasting cap was located and detonated at the surface of the ground. This condition is termed a surface burst.

The shock wave generated from the detonated blasting cap was monitored at nominal distances of 3.05, 15.2, 42.7, and 80.8 meters from the explosion point. The transducers used were piezoelectric "pencil gages"[2] oriented normal to the air shock front. The pressures thus observed were the side-on shock overpressures. A schematic of the blasting cap-pressure gage arrangement is shown in Figure 1.

After conversion of the electrical signals from the transducers from high to low impedance they were fed via coaxial cable to the recording system. The transducer outputs were usually recorded simultaneously with Tektronix-type 502A dual-beam oscilloscopes and an Ampex FR-600 tape recording system (frequency response: flat dc to 20 kHz). The oscilloscope recordings were used for rapid time-domain readout and the tape recordings for subsequent frequency domain analysis. Figure 2 shows a block diagram of the typical recording system used during this work and Figure 3 shows some representative pressure-time histories observed.

Generally, the positive pressure phase of these waves (which is nearly triangular in shape), increases in total duration with increasing range. The peak pressure decreases with increasing distance at an attenuation rate higher than for a spherically radiating acoustic wave.

The data analyzed and presented herein are from a large number of experiments conducted over a time period of several months and a broad range of outdoor temperature, humidity, and wind conditions. A total of 148 pairs of peak pressure-distance data over the range of 3.05 to 80.8 meters from the explosion point has been included in this study. The average peak pressures at each range are plotted in Figure 4. A least squares fit through these data provides the following relationship:

$$P_{max} = 0.105\ R^{-1.42}, \qquad (1)$$

where P_{max} is the peak positive pressure in bars and R is the range in meters. The straight line drawn through the graphed points on log-log coordinates in Figure 4 is a representation of Equation (1). The attenuation of amplitude with distance for a spherically expanding acoustic wave is a function of R^{-1}. At the pressure levels observed in this study the shock wave attenuation is a function of $R^{-1.42}$.

Data reported by Kingery[3] for surface burst TNT in the 4.5 to 91 metric ton range covering the pressure range from 0.1 to 3×10^{-3} bars have been fitted by the equation:

$$P = 4.26\ \lambda^{-1.407}. \tag{2}$$

λ is defined as the scaled distance:

$$\lambda = R/(W)^{1/3}, \tag{3}$$

where W is the explosive weight or yield in kilograms. The units of λ are meters/$kg^{1/3}$.

The attenuation exponents for pressure versus distance for the No. 6 electric blasting cap agree quite well with TNT data for much larger explosions (compare Eqs. (1) and (2)). An explosion yield determination then involves only the foregoing three equations. On the basis of these data, the yield of the No. 6 blasting cap is 0.39 grams of TNT.

FREQUENCY SPECTRA OF BLASTING CAPS

The pressure waves recorded for the No. 6 blasting cap are, in a sense, intermediate in form between the close-in, very high amplitude shock waves usually measured near an air burst, and the idealized N-wave often used to typify the "sonic boom" shock waves generated by supersonic aircraft. The close-in explosion shock wave is commonly fitted by the exponential Friendlander equation[4] (or a "modified Friendlander" equation) for which the frequency transform is a simple expression that represents a smooth, single-peaked spectrum[5]. The idealized N-wave is a symmetric pressure wave, with a frequency transform that can be expressed as spherical Bessel functions, and a spectrum that contains numerous higher harmonics[6-11]. The recorded pressure waves and their frequency distributions do not conform completely to either pattern, but show some characteristics of both.

The spectral energy density, E(f), of the shock waves generated by the No. 6 blasting cap was determined digitally from the squared modulus of the Fourier transform of the sample time functions of Figure 3.

$$E(f) = 10 \log_{10} \left| A(f) \right|^2, \tag{4}$$

where the amplitude spectrum, A(f), for the pressure wave of duration T is,

$$A(f) = \int_0^T p(t)\, e^{-i\omega t}\, dt. \tag{5}$$

The three sample spectra, for ranges of 3.05, 15.6, and 42.4 meters are shown in Figure 5. Pressures are normalized to $20\ \mu N/m^2$ in the spectrum level. The sampling rate was adequate for frequencies up to 10 kHz, and spectrum levels were computed at small frequency intervals so that oscillations in the spectrum were defined.

With increasing range, as the duration of the positive phase of the pressure pulse increases, the maximum energy level occurs at lower frequencies. Similarly, the overall spectrum level decreases in accordance with the decreasing pressure levels. At frequencies above the fundamental, the mean spectrum level decays at the rate of -6 dB/octave over a considerable frequency range, and then at an increasing rate for higher frequencies. For the two closer ranges, where the shock rise time is negligibly small, there is only a small increase in spectrum slope at the higher frequencies. At the 42.4 meter position, however, where the finite rise time is roughly 0.25 msec, the spectrum slope is -12 dB/octave, the value predicted for ideal N-waves with finite rise times[10,11] for frequencies above about 3 kHz.

Thus, the high-frequency end of the blasting cap spectrum, which is contributed by the triangular positive phase of the pressure pulse, is similar to that of a sonic boom shock, although the oscillations are notably damped. This initial positive pressure phase dominates the spectrum for frequencies above about 1 kHz. At lower frequencies, however, the influence of the negative phase of these asymmetric pressure pulses is apparent. At zero frequency, the spectrum level is determined by the residual impulse of the time function. From this limiting value, the level increases to a broad maximum that occurs at about 0.5 kHz for the 3.05 meter location, and moves down to about 0.2 kHz at the 42.4 meter range.

Granström[12] has pointed out that the waveform of an airblast pressure-time curve changes in character as the wave propagates outward. The exponential pressure decay that occurs at short ranges is gradually replaced by a rectilinear waveform at greater ranges and the areas of the positive and negative phase of the wave tend more and more to equalize. In the example shown in reference (12), the rectilinear shape obtains at distances beyond about 5 m from a 1 kg TNT charge. With the 0.39 g TNT equivalent charge weight estimated for the blasting cap from the peak pressure values, the comparable transition distance is only about 0.4 m, which is closer than the nearest measurements made during these tests. And, indeed, over the range of the measurements, the observed blasting cap pressure waves can be quite well represented as a positive triangular phase followed by a parabolic negative phase. Although the records do not permit accurate measurement of the negative phase durations, the negative phase is roughly twice as long as the positive phase of the waves. For these time dimensions, the areas of the triangular and parabolic portions of the wave are equal if the maximum negative pressure is 3/8 of the maximum positive pressure. The average value of this ratio, (P_{min}/P_{max}), which can be measured with fair accuracy, is almost exactly 3/8. If the rise time is neglected, the energy density spectra can be approximated analytically by the transform of the time function expressed as the sum of a triangle of initial pressure P_{max} and duration τ and, at time $(t-\tau)$, a parabola of duration $(2L)$. With the subscripts 1 and 2 indicating the positive (triangular) and negative (parabolic) phases of the pressure pulse, the time and frequency transform pair is,

$$f(t) = f_1(t) + f_2(t-\tau) \tag{6}$$

$$g(\omega) = g_1(\omega) + g_2(\omega)\, e^{-i\omega\tau} \tag{7}$$

$$\text{where } f_1(t) = 0 \qquad t < 0$$

$$= P_{max}\,(1 - t/\tau) \qquad 0 < t \leq \tau \tag{8}$$

$$\text{and } f_2(t) = P_{min}\left[1 - \frac{(L-t)^2}{L^2}\right], \qquad \tau < t \leq 2L$$

$$= 0 \text{ elsewhere.} \tag{9}$$

The resulting analytical energy spectrum is a sum of the individual spectra, I and N, of the two segments of the wave, plus a cross-products term X:

$$\left|A(\omega)\right|^2 = I + N + X \tag{10}$$

In terms of the pressure and time variables, the contribution of the positive phase, I, is

$$I = \frac{(P_{max}\ \tau)^2}{(\omega\tau)^4} \left[(1-\cos\ \omega\tau)^2 + (\sin\ \omega\tau - \omega\tau)^2 \right]. \tag{11}$$

The contribution of the negative phase, N, is

$$N = \frac{8(p_{min}\ L)^2}{(\omega L)^6} \left[1+\omega^2L^2+(\omega^2L^2-1)\cos(2\omega L)-2\omega L\ \sin(2\omega L) \right] \tag{12}$$

and the cross-products term is:

$$X = V \left[\omega L\ \cos(\omega L)-\sin(\omega L) \right]\ x\ \left[\cos(\omega L)-\cos\ \alpha\ -\ \omega\tau\ \sin\ \alpha \right] \tag{13}$$

where $\alpha = \omega(\tau+L)$ (14)

and $V = 8(P_{max}\tau)\ (p_{min}L)/(\omega\tau)^2(\omega L)^3$ (15)

As noted above, for the pressure waves reported here, P_{min} and L can be replaced by (3/8 P_{max}) and τ, respectively, in Equations (11)-(15). The more general form is retained here, however, to facilitate use of the equations for other conditions.

In Figure 6, the analytical spectrum for the total pulse (dashed line) determined from Equation (10) is compared with the measured spectrum for the pressure pulse recorded at 15.6 meters. Although the analytical spectrum cannot reproduce the measured oscillations (which are due in large part to random reflections included in the measured pressure waves), the salient features of the analytical (total pulse) and measured spectra are in excellent agreement. The spectrum for the positive phase alone (Eq. (11)) is an adequate mean value for higher frequencies.

There is similar good agreement between analytical and measured spectra for the other two ranges (3.05 and 42.4 meters) shown in Figure 5, provided a correction for finite rise time is included at the longer range. The necessary correction is simply a replacement of the calculated values by a line of constant, -12 dB/octave slope for frequencies above (1/rise time).

SUMMARY

The time-domain behavior of the shock wave generated in air by a commercial No. 6 electric blasting cap and its yield relative to TNT have been established. The peak pressure-distance attenuation exponent is observed to be the same for this small explosion source as for TNT explosions as large as 91 metric tons. Even at the low pressures measured. the waves maintain their characteristic shape and are attenuating more rapidly with distance than acoustic waves.

The distribution of the spectral energy density for these typical explosion wave shapes has been compared with that of the "sonic boom" N wave. The presence of a long duration slowly varying negative pressure phase in the explosion wave is the major difference between these waves. This difference primarily influences the low frequency portion of the spectrum.

The explosion-generated shock wave when considered as a triangular positive phase and a parabolic negative phase provides a theoretical energy density spectrum which compares favorably with the spectrum of an actual airblast pulse.

REFERENCES AND FOOTNOTES

[1] Manufactured by the Olin Mathieson Company, Explosive Content: Mercury Fulminate - 0.117 gms, Black Powder - 0.078 gms, Lead Azide - 0.29 gms, and RDX - 0.39 gms.

[2] Manufactured by Atlantic Research Corporation, Model No. LC-33.

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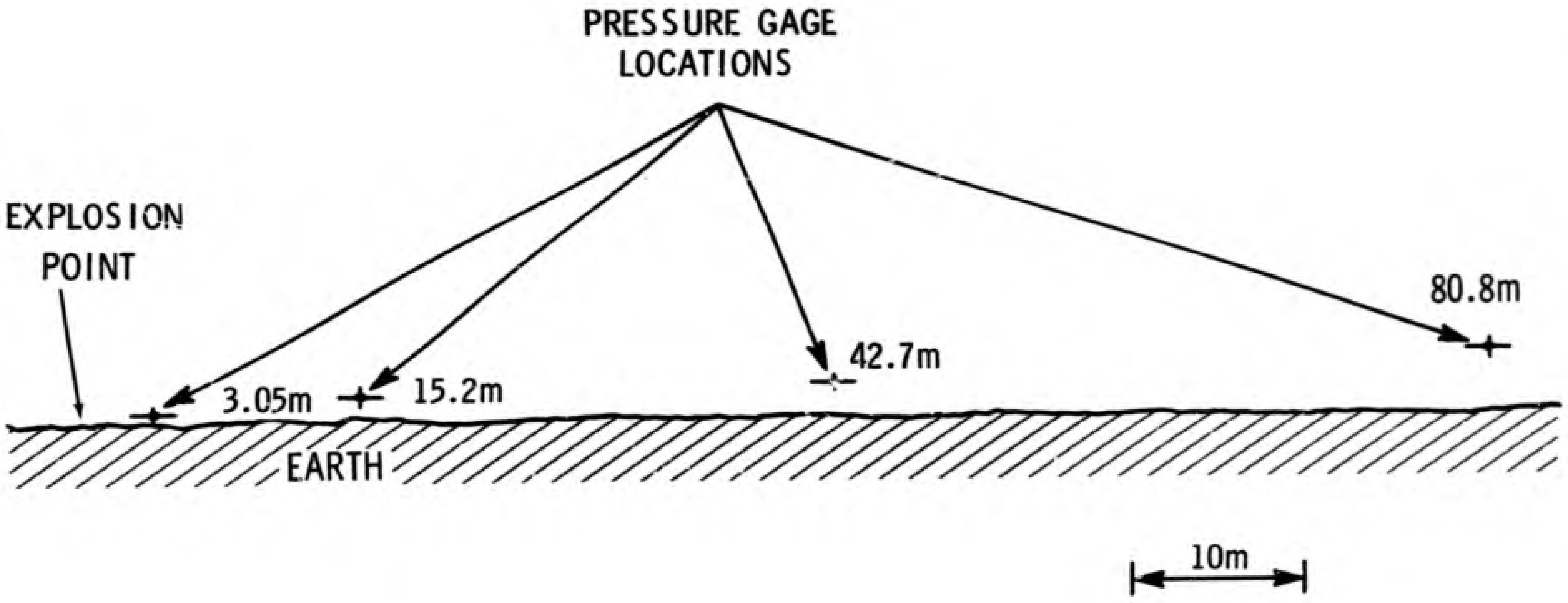

Figure 1. Schematic diagram of experimental arrangement

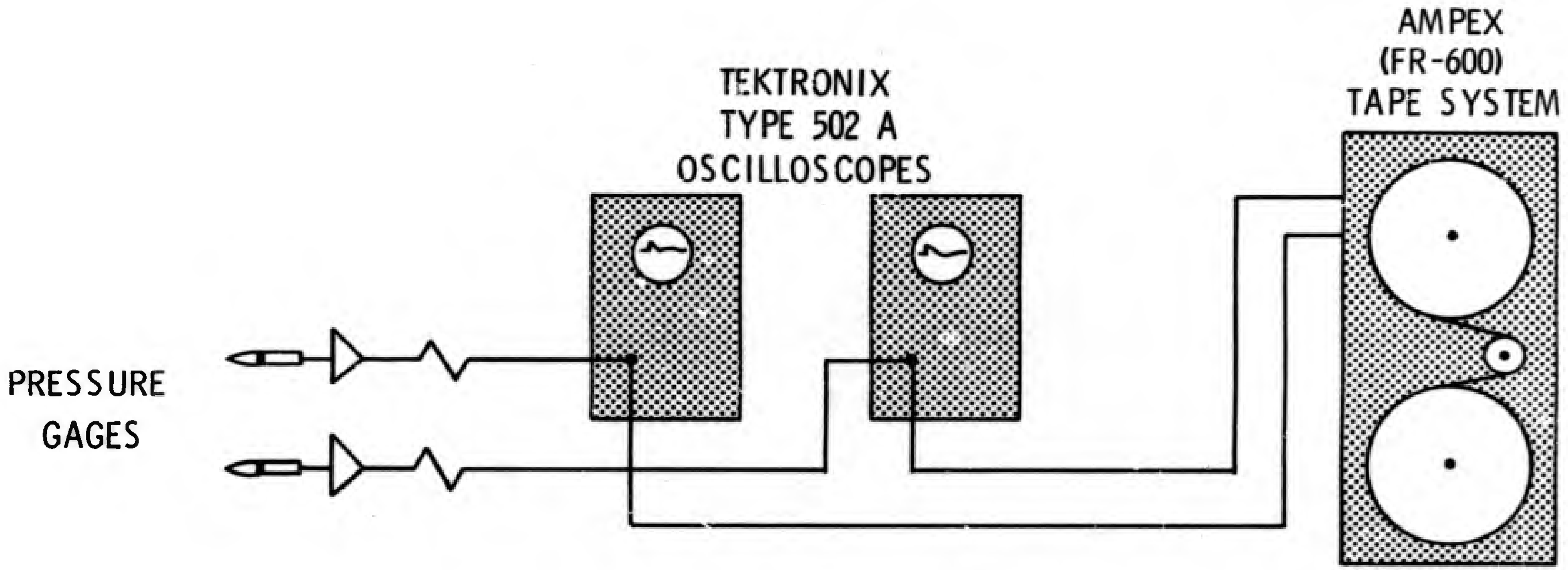

Figure 2. Block diagram of recording system

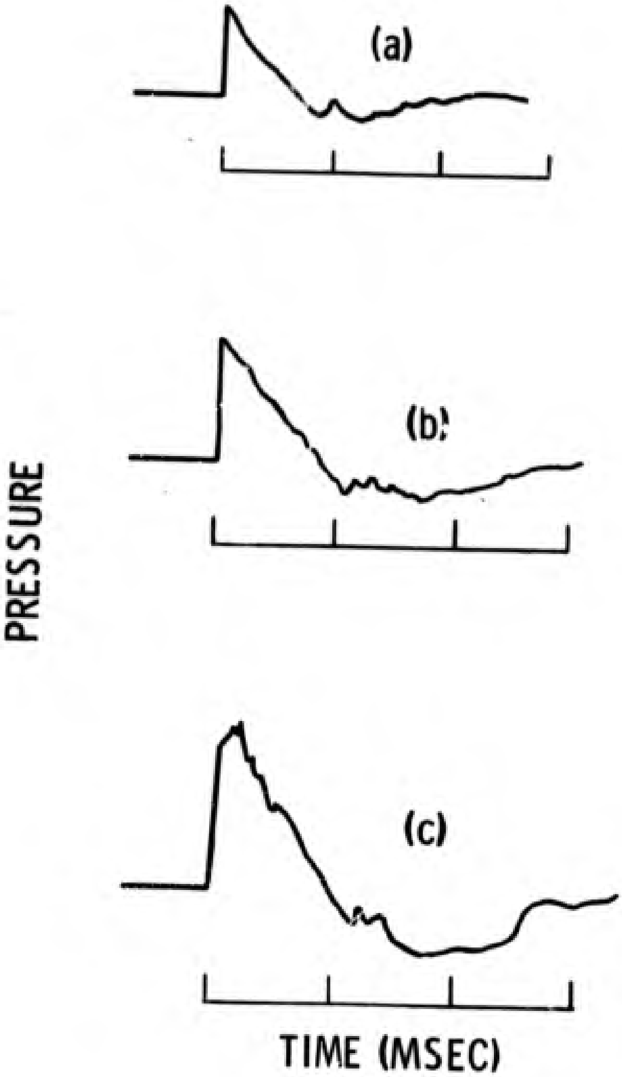

Figure 3. Representative pressure-time histories observed at ranges of (a) 3.05 m, (b) 15.6 m and (c) 42.4 m. Peak overpressures at these ranges are: (a) 2.26×10^{-2} bars, (b) 2.74×10^{-3} bars and (c) 5.32×10^{-4} bars.

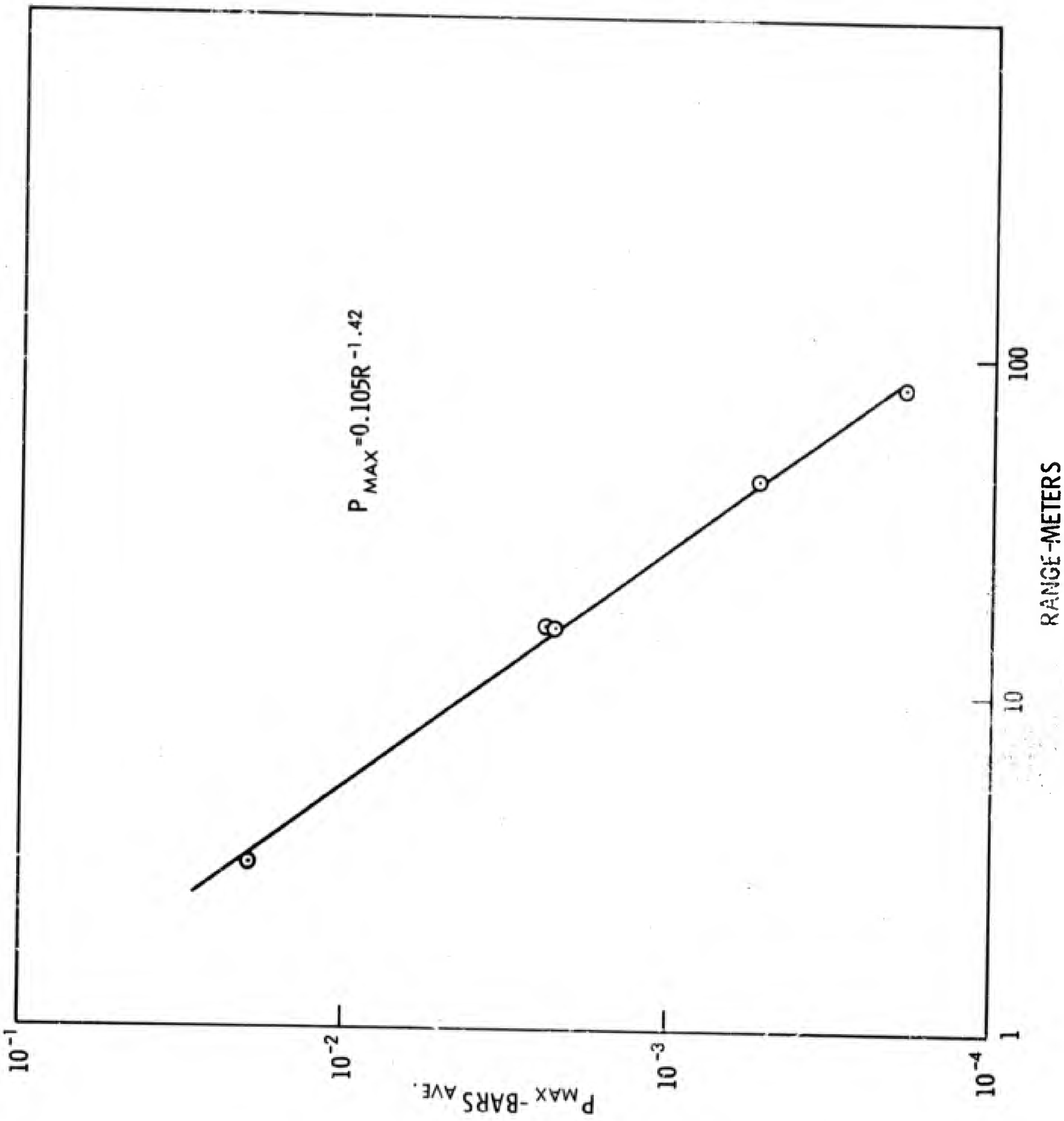

Figure 4. Peak overpressure (bars) versus range (meters). Plotted points show average values at each range and represent a total of 148 sets of measurements.

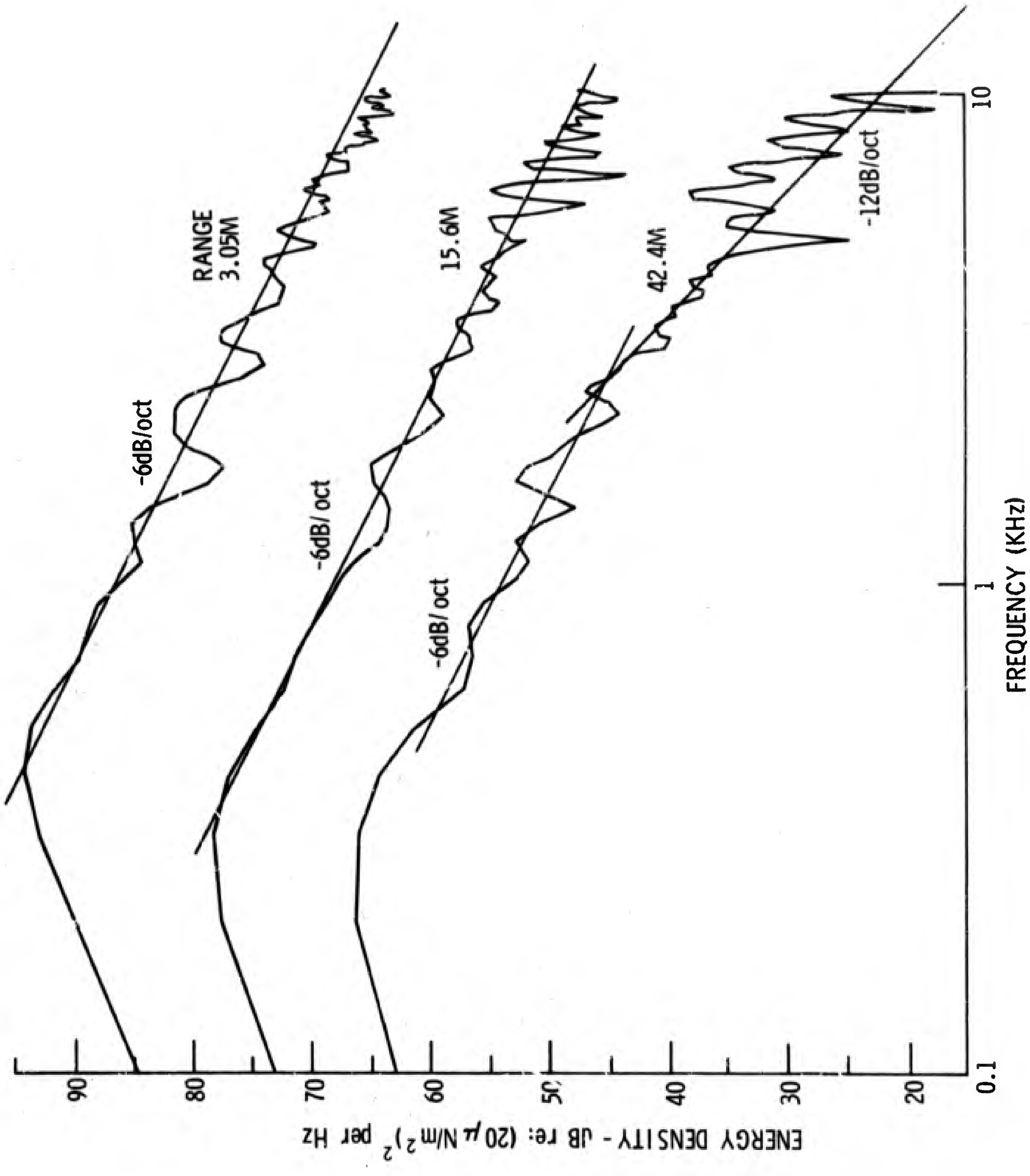

Figure 5. Energy density spectra of pressure waves measured at ranges of (a) 3.05 m, (b) 15.6 m and (c) 42.4 m.

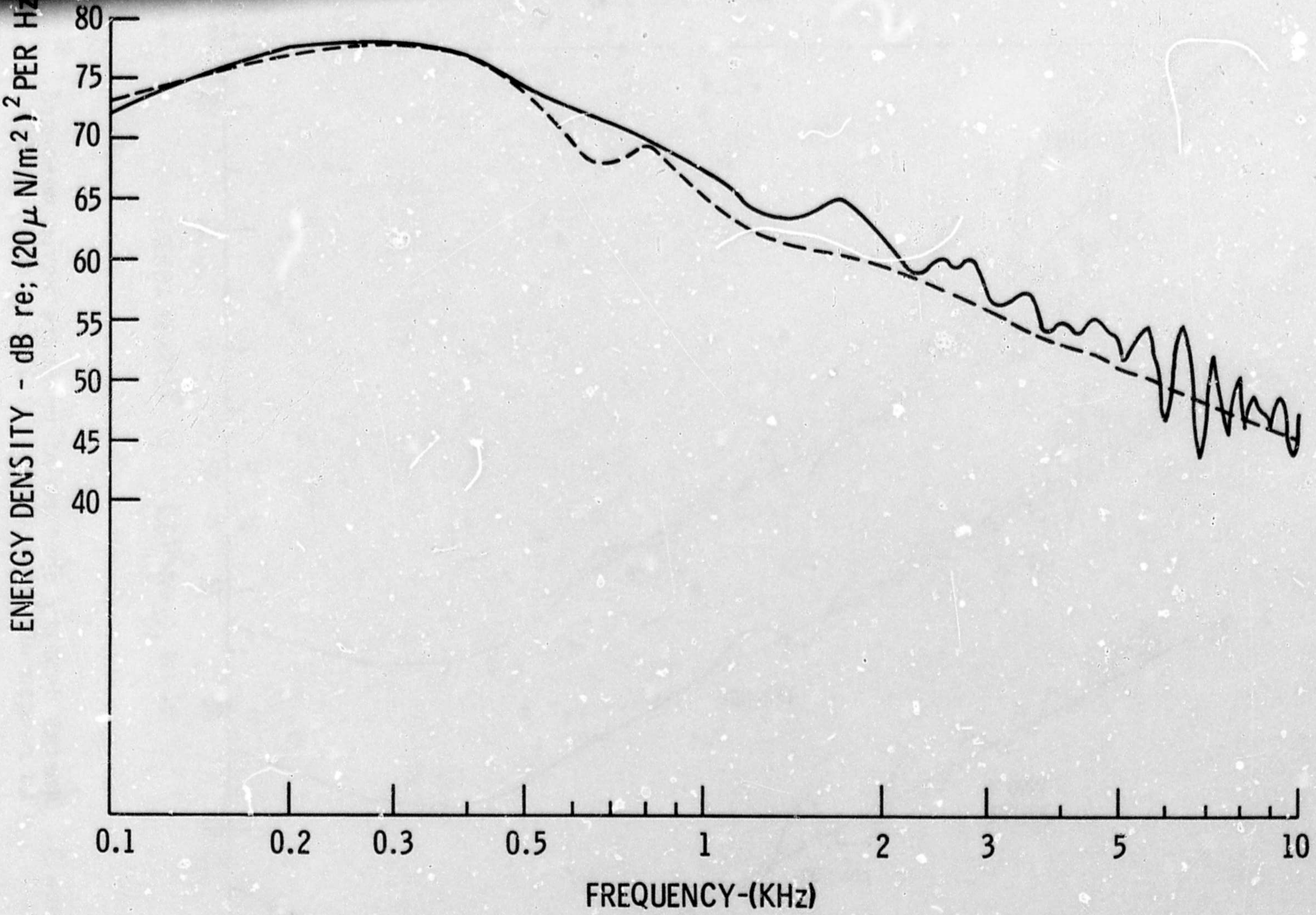

Figure 6. Energy density spectrum of pressure pulse at 15.6 m range. Solid line is measured spectrum and dashed line is approximation with Equation (10).