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insert change; write on cover 'Change 2 inserted'  
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Change 2  
8 September 1964  
1 page

*J. Glenn*  
By direction

This publication is changed as follows:

19 Oct 1964

Downgrade classification of pentolite data from CONFIDENTIAL  
to UNCLASSIFIED; specifically

- (a) Pentolite similitude equations for  $p_m$ , E, I, and  $\theta$  given in the Abstract and on Page 6.
- (b) The nomograph for pentolite (Figure 8).

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Insert this change sheet between the cover and the title page of your copy.

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REVISED SIMILITUDE EQUATIONS FOR THE UNDERWATER SHOCKWAVE PERFORMANCE OF PENTOLITE AND HBX-1 (U)

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REVISED SIMILITUDE EQUATIONS FOR THE UNDERWATER  
SHOCKWAVE PERFORMANCE OF PENTOLITE AND HBX-1 (U)

by  
M. A. Thiel

Reviewed by: C. R. Niffenegger

Approved by: E. Swift, Jr., Chief  
Underwater Explosions Division

ABSTRACT: All available data obtained from spherical and squat cylindrical HBX-1 and pentolite charges fired at the Naval Ordnance Laboratory and the Woods Hole Oceanographic Institution were used to determine revised similitude equations for underwater shockwave parameters. The revised equations are: HBX-1,

$$P_m = 2.38 \times 10^4 \left(\frac{W^{1/3}}{R}\right)^{1.15}, \quad E = 2.96 \times 10^3 W^{1/3} \left(\frac{W^{1/3}}{R}\right)^{2.00},$$

$$I = 1.57 W^{1/3} \left(\frac{W^{1/3}}{R}\right)^{0.85}, \quad \theta = 0.049 W^{1/3} \left(\frac{W^{1/3}}{R}\right)^{-0.29}; \text{ pentolite,}$$

$$P_m = 2.35 \times 10^4 \left(\frac{W^{1/3}}{R}\right)^{1.14}, \quad E = 2.66 \times 10^3 W^{1/3} \left(\frac{W^{1/3}}{R}\right)^{2.04},$$

$$I = 1.48 W^{1/3} \left(\frac{W^{1/3}}{R}\right)^{0.91}, \quad \theta = 0.052 W^{1/3} \left(\frac{W^{1/3}}{R}\right)^{-0.23}.$$

Each equation represents an average and so when plotted lies in the band formed by the curves of previously obtained similitude equations. Nomographs for obtaining shockwave parameters are included (c).

EXPLOSIONS RESEARCH DEPARTMENT  
U. S. NAVAL ORDNANCE LABORATORY  
WHITE OAK, MARYLAND



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1 February 1961

The work described in this report is part of the continuing program of investigation of the underwater performance of explosive mixtures, under Task RUME-3-E-002/2121/ F008-10-004. Results shown here represent the best absolute values available at present for the underwater explosion parameters of HBX-1 and pentolite, which are used as standards of underwater explosive performance. The values for pentolite supersede those given in NAVORD Report 2575. The nomographs given here are also included as a revision in NAVORD Report 2986, "Explosion Effects Data Sheets".

W. D. COLEMAN  
Captain, USN  
Commander



C. J. ARONSON  
By direction

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REVISED SIMILITUDE EQUATIONS FOR THE UNDERWATER  
SHOCKWAVE PERFORMANCE OF PENTOLITE AND HBX-1 (U)

1. INTRODUCTION

A large amount of underwater shockwave data for HBX-1 and pentolite has been accumulated in the past 15 years from the explosives testing programs of the Naval Ordnance Laboratory (NOL) and the Woods Hole Oceanographic Institution (WHOI). In the past the data have been treated in small groups, and similitude equations have been derived from each firing program. This has led to some discrepancies between various sets of results. A review of the available data was therefore made in order to resolve these discrepancies and to provide consistent and reliable values of underwater parameters for pentolite and HBX-1. In this report the method of treating the data is given, and new similitude equations and nomographs for peak pressure, time constant, impulse, and energy of pentolite and HBX-1 are presented.

2. DISCUSSION OF DATA

2.1 Data Chosen: All data used herein were obtained from spherical and squat cylindrical charges; data from elongated charges were excluded. Charge weights ranged from 0.5 to 80 pounds. Pressure-time measurements were made at reduced distances,  $R/W^{1/3}$  (where R is the charge-to-gage distance in feet and W is the charge weight in pounds), ranging from approximately 1.2 to 25. The instrumentation used at NOL is described in Reference (a)\* and modifications to it are described in References (b - e). The equipment used at WHOI is described in Reference (f). Most of the data were obtained by NOL. Table I describes briefly the data used for this study.

\*The list of references is on page 7.

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TABLE I  
SOURCES OF DATA

Reference	Source	Charge Wt. (lbs)	Charge Shape	Gage Dia. (in.)	Charge-to- Gage Dist. (ft.)	Number of*** Data Points
HBX-1						
(g)	WHOI	50	Sphere	1/4, 1/2	5-100	12
(g)	WHOI	80	Sphere	1/4, 1/2	5-100	12
(k)	NOL	1.1	Cyl.	1/4	2-6	3
(d)	NOL	45	Cyl.	1/4, 3/8*	6-50	9
(l)	NOL	45	Cyl.	1/4, 3/8*	6-50	8
(n)	NOL	45	Cyl.	1/4, 3/8*	6-50	8
(o)	NOL	45	Cyl.	1/4, 3/8*	6-50	8
(p)	NOL	47	Cyl.	1/4, 3/8*	6-40	4
(q)	NOL	46	Cyl.	1/2	6-50	8
(r)	NOL	10	Cyl.	1/4, 3/8**	4.5-45.5	4
(r)	NOL	30	Cyl.	1/4, 3/8**	7-48	4
(r)	NOL	50	Cyl.	1/4, 3/8**	9-50	4
(s)	NOL	10	Cyl.	1/4	4.5-43.5	4
Pentolite						
(i)	WHOI	51	Sphere	1/4, 1/2	12-100	12
(i)	WHOI	80	Sphere	1/4, 1/2	12-100	12
(h)	WHOI	0.55	Sphere	1/4	1.4-1.7	2
(j)	WHOI	1.1	Sphere	1/4, 3/8	1-7	45
(j)	WHOI	2.3	Sphere	1/4, 3/8	1-7	7
(m)	NOL	0.66	Cyl.	1/4	2-6	3
(m)	NOL	1.0	Cyl.	1/4	2-6	3
(m)	NOL	1.32	Cyl.	1/4	2-6	3
(m)	NOL	1.65	Cyl.	1/4	2-6	3
(m)	NOL	44	Cyl.	1/4, 3/8*	6-50	8

\*Tests on which incorrect slope of pressure-distance relationship was obtained; 1/4 in. gages at distances close to the charge and 3/8 in. gages at far out positions. See paragraph 2.3.

\*\*1/4 and 3/8 in. gages paired at each distance.

\*\*\*Each data point was the average of 2-4 individual records.

2.2 Parameters: The shockwave parameters which were included in this study are:

$p_m$  The pressure at the shock front. (psi)

$\theta$  The time constant; the time at which  $p = p_m/e$ . (The first portion of the shockwave is approximately an exponential until this time.) (milliseconds)

I The impulse =  $\int_0^{5\theta} p dt$  (psi-sec)

E The energy =  $\frac{1 - (1.7 \times 10^{-6})}{\rho_o c_o} \int_0^{5\theta} p^2 dt$  (in.-lbs/in.<sup>2</sup>)

where  $\rho_o c_o = 5.14 + 0.0144 t^0$  Cent.

The values of each parameter obtained from the original records were accepted substantially as reported; none of the records was re-read.

2.3 Effect of Gage Size: All of the pressure-time recordings were made with tourmaline piezoelectric gages whose diameters were 1/4, 3/8, or 1/2 inch. Different combinations of gage sizes were used from time to time, and the particular arrangement used seemed to correlate with variations in the experimental results.\* These variations appeared in the NOL data.

Prior to 1954 NOL pressure-time recordings were made with small gages, usually 1/4-in., at positions close to the charge, and slightly larger gages, usually 3/8-in., at the farther positions. The peak pressure-distance similitude relationship so obtained showed a considerably different slope (exponent) from the earlier WHOI relationships. Examination of the data showed that a separate similitude equation could be derived for each gage size with an exponent having almost the same value as that in the corresponding similitude equation obtained by WHOI. Thus while each size of gage was yielding a consistent result by itself, combining the close-in results with the farther-out results yielded a slope in disagreement with the previous work.

A careful study was made of the effect of gage size on the shockwave measurements. (See Appendix C of Reference (r).) It was found that while there is an effect, it is of such small magnitude that it could not account for the differences observed between the large and small gage results. Although the cause of the differences has not been found, gage size was taken into account in the grouping of the data for analysis.

\*While the discussion below is restricted to peak pressure variations, similar results are found in the impulse and energy data.

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Since 1954 all NOL data have been taken using two sizes of gage at each position.

3. TREATMENT OF DATA

3.1 General: Each of the parameters was treated in the same general manner. The data were separated by gage size into groups and then each group was plotted on log-log graph paper. From these plots slopes and similitude equations were determined. For each parameter, several slopes were obtained which were identical or nearly so. An average slope was then used in drawing the best line through all the data points on one plot. The procedure is illustrated with the HBX-1  $p_m$  data in the following section.

3.2 HBX-1 Peak Pressure: HBX-1  $p_m$  data were divided into six groups, as follows: NOL 1/4-in. gages, NOL 3/8-in. gages, NOL 1/2-in. gages, NOL 1/4 and 3/8-in. gages paired, and WHOI gages. Figure 1 shows the 1/4-in., 3/8-in., and 1/2-in. data plotted. The data from gages of unknown size were not used; each of the other groups was plotted on log-log paper and an equation derived. The equations obtained were:

$$\begin{aligned} p_m &= 2.40 \times 10^4 \left( \frac{w^{1/3}}{R} \right)^{1.15} && 1/4\text{-in.} \\ &= 2.10 \times 10^4 \left( \frac{w^{1/3}}{R} \right)^{1.15} && 3/8\text{-in.} \\ &= 2.24 \times 10^4 \left( \frac{w^{1/3}}{R} \right)^{1.15} && 1/2\text{-in.} \\ &= 2.56 \times 10^4 \left( \frac{w^{1/3}}{R} \right)^{1.15} && 1/4 - 3/8\text{-in. paired} \\ &= 2.48 \times 10^4 \left( \frac{w^{1/3}}{R} \right)^{1.15} && \text{WHOI} \end{aligned}$$

The exponent (1.15) representing the slope of the log-log  $p_m$  vs  $\frac{w^{1/3}}{R}$  plot is the same for the above equations.

To obtain the final over-all equation, all data points were plotted on log-log paper and the best line drawn to a slope of 1.15. Figure 2 shows this plot. The resulting equation is:

$$p_m = 2.38 \times 10^4 \left( \frac{w^{1/3}}{R} \right)^{1.15}$$

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The slopes obtained from such sets of plots occasionally were not identical; the maximum variation was 3 - 4%. The best slope was then determined by taking a weighted average of the slopes of the different plots.

The other parameters were treated in the same manner with the exceptions noted below.

3.3 Energy and Impulse: The NOL shockwave records were integrated to 50 while WHOI records were integrated to 6.70. To make the data comparable, the WHOI integrations were corrected to 50. This was done by multiplying energy values by 0.98 and impulse values by 0.92. The factors are from Figures 9.4 and 9.6 of Reference (t). While these factors were determined from a study of HBX-2 records, they are also applicable here.

3.4 Time Constant: WHOI time constant data were not used since NOL and WHOI used different methods for determining time constant.\* While this results in slight differences in  $\theta$ , either set of values may be considered reliable within the limits of accuracy, and the difference should have only a slight effect on the derived parameters of energy and impulse.

4. RESULTS

4.1 Similitude Equations: The similitude equations for HBX-1 and pentolite obtained in the manner described are:

$$\begin{aligned} \text{HBX-1: } p_m &= 2.38 \times 10^4 \left( \frac{W^{1/3}}{R} \right)^{1.15} \\ E &= 2.96 \times 10^3 W^{1/3} \left( \frac{W^{1/3}}{R} \right)^{2.00} \\ I &= 1.57 W^{1/3} \left( \frac{W^{1/3}}{R} \right)^{0.85} \\ \theta &= 0.049 W^{1/3} \left( \frac{W^{1/3}}{R} \right)^{-0.29} \end{aligned}$$

\*At WHOI the time constant was read from an enlargement of the pressure-time record. At NOL the pressure-time records were plotted on semi-log paper and the time constant was determined from the line drawn through the initial decay of the record.

$$\text{Pentolite: } P_m = 2.35 \times 10^4 \left( \frac{W^{1/3}}{R} \right)^{1.14}$$

$$E = 2.66 \times 10^3 W^{1/3} \left( \frac{W^{1/3}}{R} \right)^{2.04}$$

$$I = 1.48 W^{1/3} \left( \frac{W^{1/3}}{R} \right)^{0.91}$$

$$\theta = 0.052 W^{1/3} \left( \frac{W^{1/3}}{R} \right)^{-0.23}$$

4.2 Discussion of Equations: The most widely used HBX-1 and pentolite similitude equations have been those of References (g) and (i) which are the equations reported in NavOrd Report 2986. These equations were obtained at WHOI. There was no gage size effect in the data used to derive the equations. The revised equations represent an average of all currently available data with allowances made for gage size effect. In Table II are shown coefficients and exponents of both sets of equations for comparison.

TABLE II

COMPARISON OF REVISED AND NAVORD 2986 SIMILITUDE EQUATIONS

	HBX-1				Pentolite				
	$P_m$	E	I	$\theta$	$P_m$	E	I	$\theta$	
Coefficient	2986	2.48	3.55	1.80	0.055	2.25	3.27	2.18	0.060
	Revised	2.38	2.96	1.57	0.049	2.35	2.66	1.48	0.052
Exponents	2986	1.15	2.06	0.87	-0.27	1.13	2.12	1.05	-0.18
	Revised	1.15	2.00	0.85	-0.29	1.14	2.04	0.91	-0.23

The revised and the NavOrd 2986 equations are plotted in Figures 3, 4, 5, and 6. The absolute difference between the two sets of equations at



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different reduced distances can be seen directly. Peak pressure and reduced energy show lesser differences than do reduced impulse and reduced time constant. For peak pressure the difference between the two sets of equations is not significant. The difference shown by the other parameters is probably not significant for practical purposes.

The similitude equations found in References (d), (l), (m), (n), (o), and (p) should not be used. These equations came from data in which a gage size effect was present. The gage size effect resulted in incorrect exponents in the similitude equations.

The revised equations may change in the future. Because of errors of measurement inherent in the experimental technique and lack of absolute reproducibility of small charge results, these equations may well be modified as more series are shot.

4.3 Nomographs: Figures 3 and 4 are nomographs for the shockwave parameters based on the new similitude equations.

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- (d) "The Effect of Aluminum on Underwater Explosive Performance: Shockwave Parameters from 50-Lb Charges", Jean A. Goertner et al, NAVORD Report 2368, 1 March 1952, Confidential.
- (e) "Underwater Shockwave Parameters for TNT", J. P. Slifko and T. E. Farley, NAVORD Report 6634, 1 June 1959, Unclassified.
- (f) "The Measurement of Underwater Explosions from Service Weapons at the Underwater Explosives Research Laboratory (UERL)", J. S. Coles, NDRS Report A-362, OSRD Report 6240, March 1946, Confidential.
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- (i) Division 2 Interim Report on "Underwater Explosives and Explosions", UE-32 OSRD 4874, 15 March 1945 - 15 April 1945, Confidential.
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- (k) "The Effect of Aluminum on Underwater Explosive Performance: Shockwave Parameters from 1-Lb Charges", R. W. Astheimer, E. A. Christian, and E. Swift, Jr., NAVORD Report 2317, 1 January 1952, Confidential.
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- (m) "Underwater Explosion Parameters for 50-50 Pentolite", Jean A. Goertner and E. Swift, Jr., NAVORD Report 2575, 15 July 1952, Confidential.

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- (n) "Underwater Performance of Explosives Containing Ammonium Perchlorate, II", Jean A. Goertner and C. R. Niffenegger, NAVORD Report 2736, 1 January 1953, Confidential.
- (o) "Underwater Performance of Explosives Containing Ammonium Perchlorate, III", E. A. Christian and C. R. Niffenegger, NAVORD Report 3563, 1 November 1953, Confidential.
- (p) "Underwater Performance of Explosives Containing Ammonium Perchlorate, IV. Preliminary Results from Several Mixtures", E. A. Christian, NAVORD Report 3728, 10 June 1954, Confidential.
- (q) "The Underwater Performance of Three Explosives Containing TNETB", C. R. Niffenegger and E. Swift, Jr., NAVORD Report 3782, 15 July 1954, Confidential.
- (r) "Underwater Performance of Explosives Containing Ammonium Perchlorate, V. Review of Available Data", E. A. Christian and C. R. Niffenegger, NAVORD Report 3897, 1 February 1955, Confidential.
- (s) "Comparisons of the Underwater Power of Explosives in Small Charges: V. Miscellaneous One-Lb and Ten-Lb Charges", E. A. Christian and M. A. Thiel, NAVORD Report 4301, 1 September 1956, Confidential.
- (t) "Underwater Free-Field Pressures to Just Beyond Target Location", C. J. Aronson et al, Operation WIGWAM, Project 1.2, WT-1005, 27 May 1957, Confidential Formerly Restricted Data

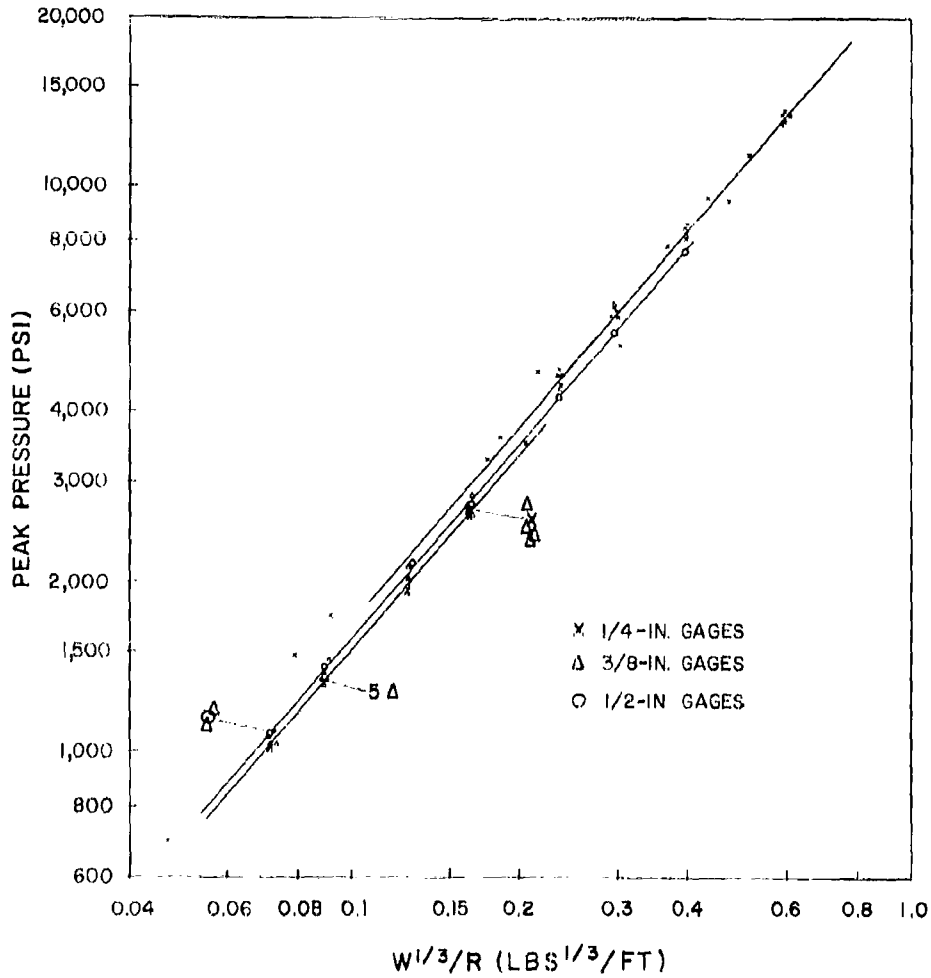


FIG. 1 PEAK PRESSURE VS W<sup>1/3</sup>/R  
FOR 1/4, 3/8, AND 1/2-IN. GAGES  
NOL HBX-1 DATA

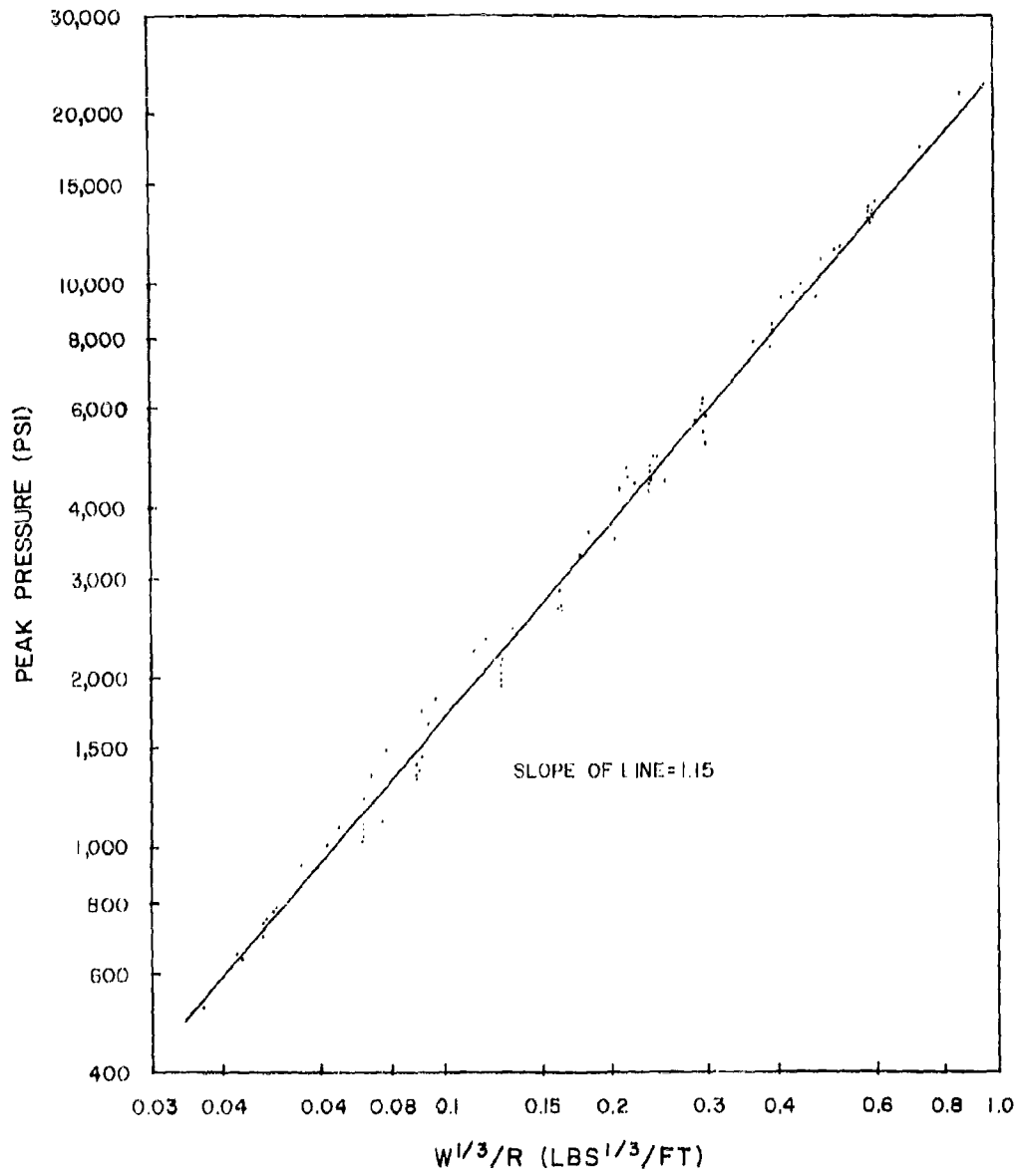


FIG. 2 PEAK PRESSURE VS  $W^{1/3}/R$   
ALL HBX-I DATA

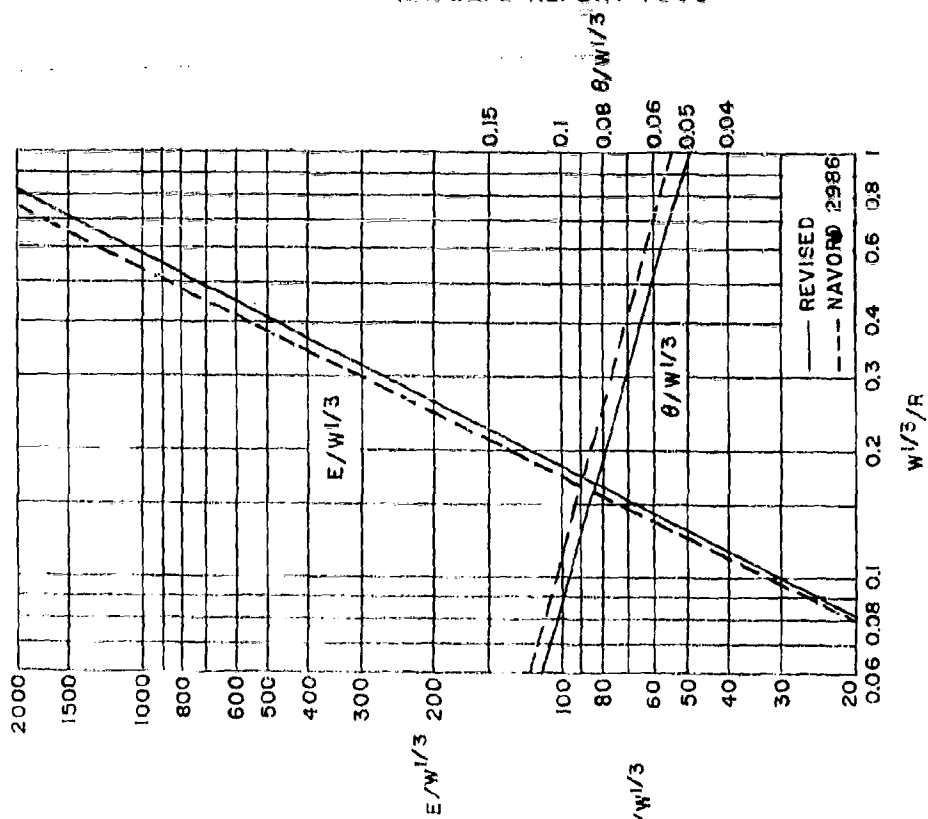


FIG. 4 COMPARISON OF REVISED AND NAVORD 2986 HBX-1 SIMILITUDE EQUATIONS -  $E/W^{1/3}$  AND  $\theta/W^{1/3}$

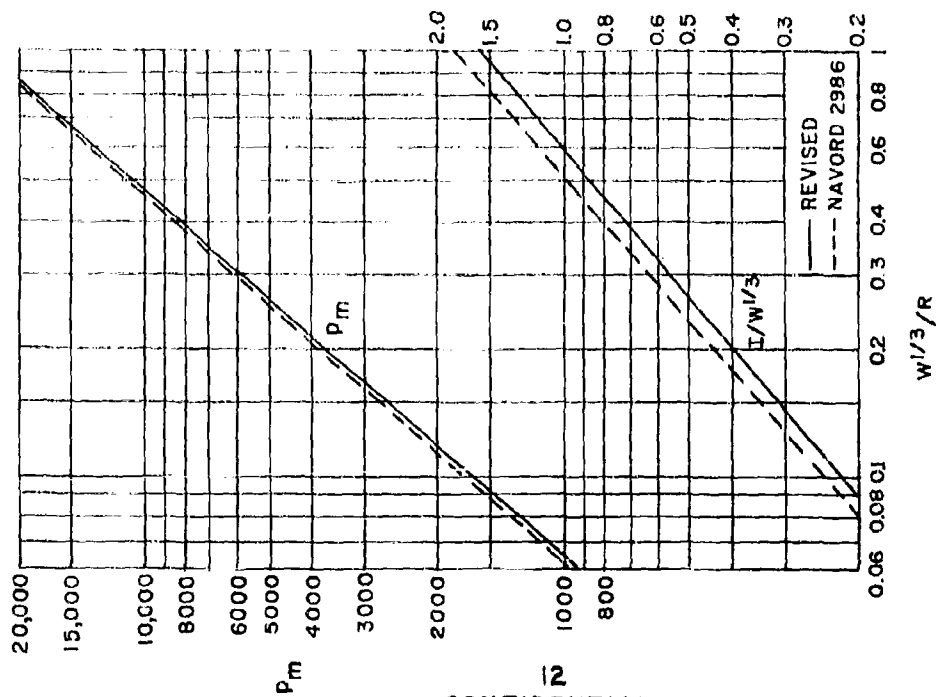


FIG. 3 COMPARISON OF REVISED AND NAVORD 2986 HBX-1 SIMILITUDE EQUATIONS -  $P_m$  AND  $I/W^{1/3}$

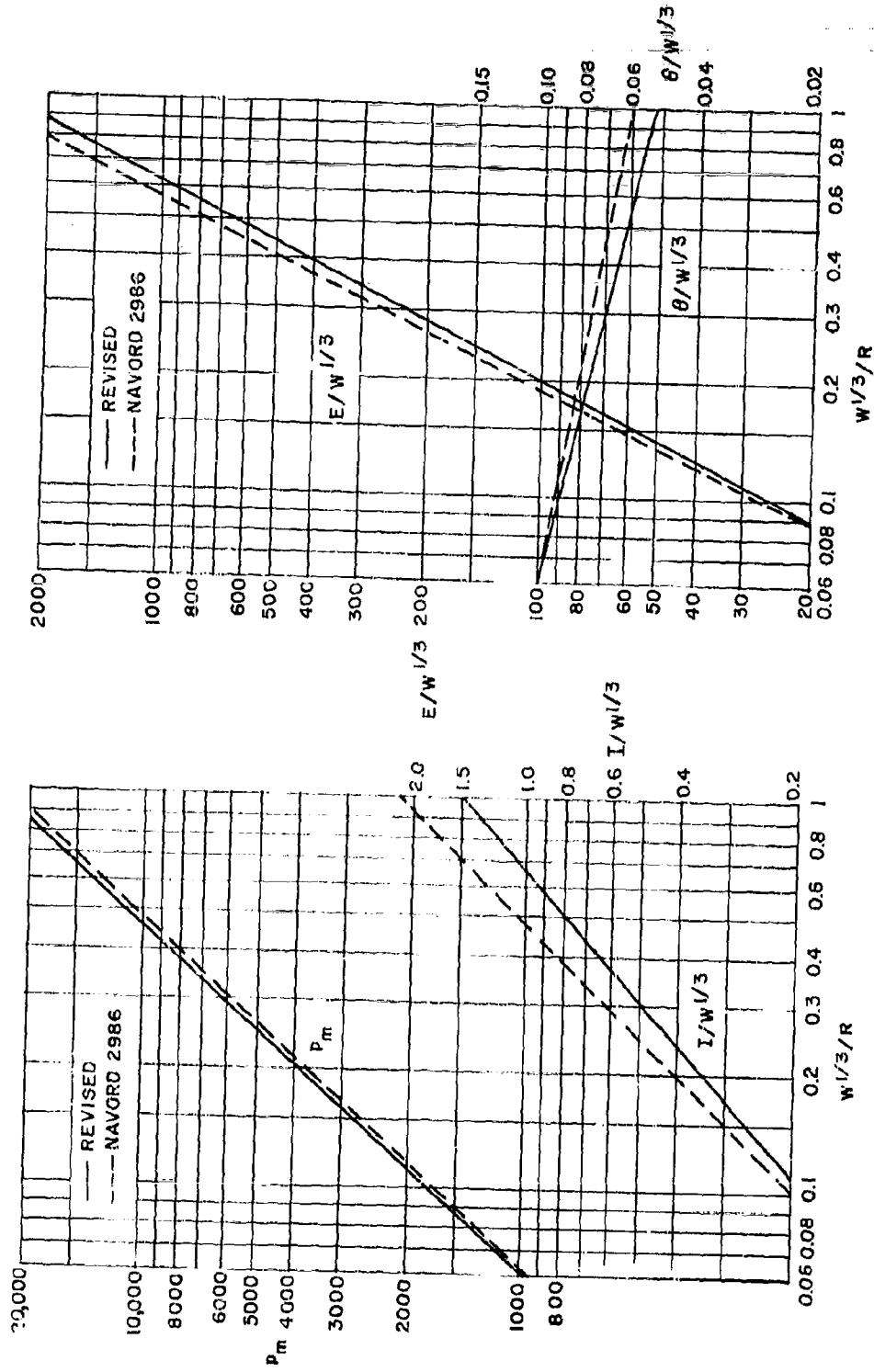
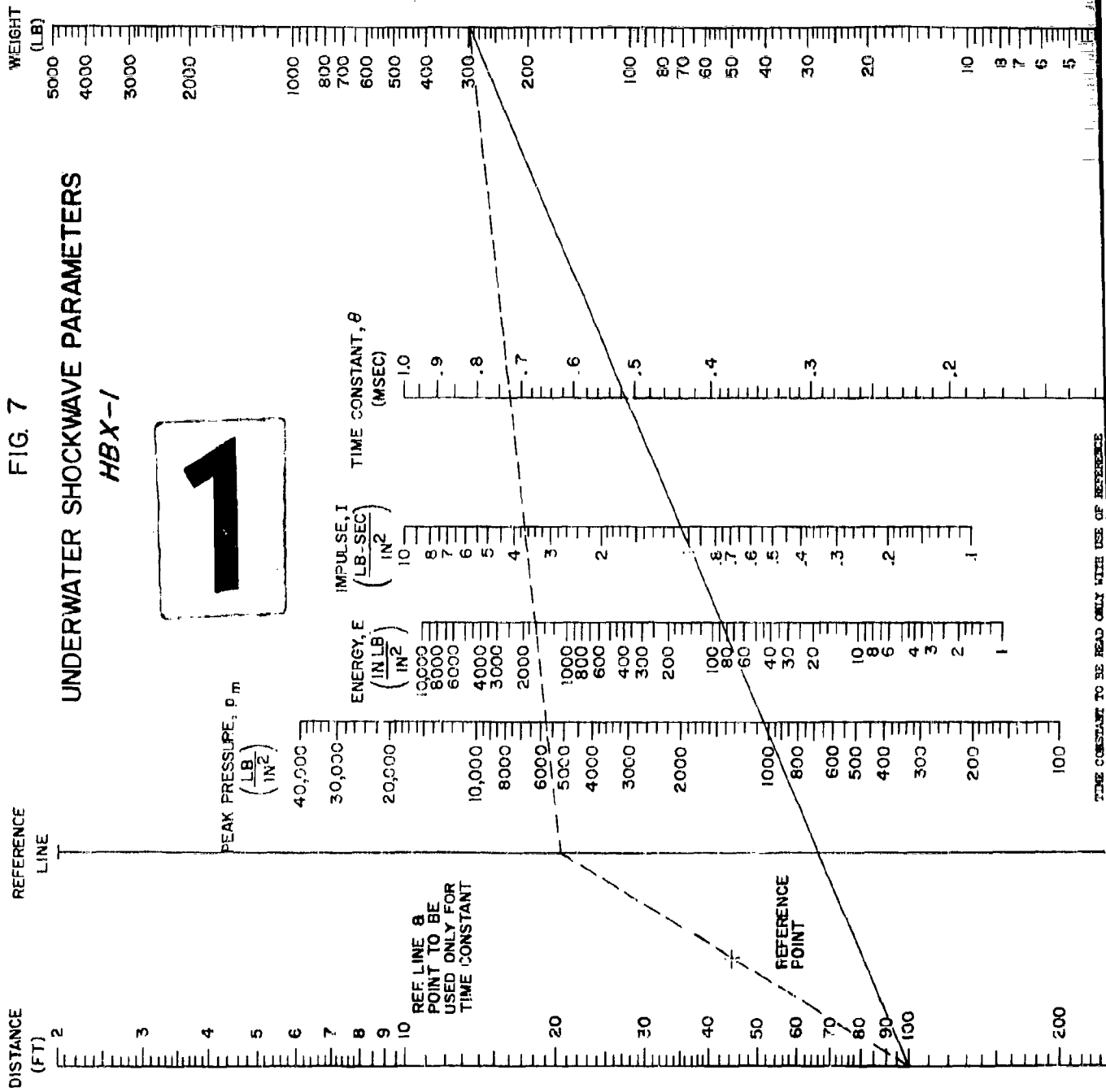


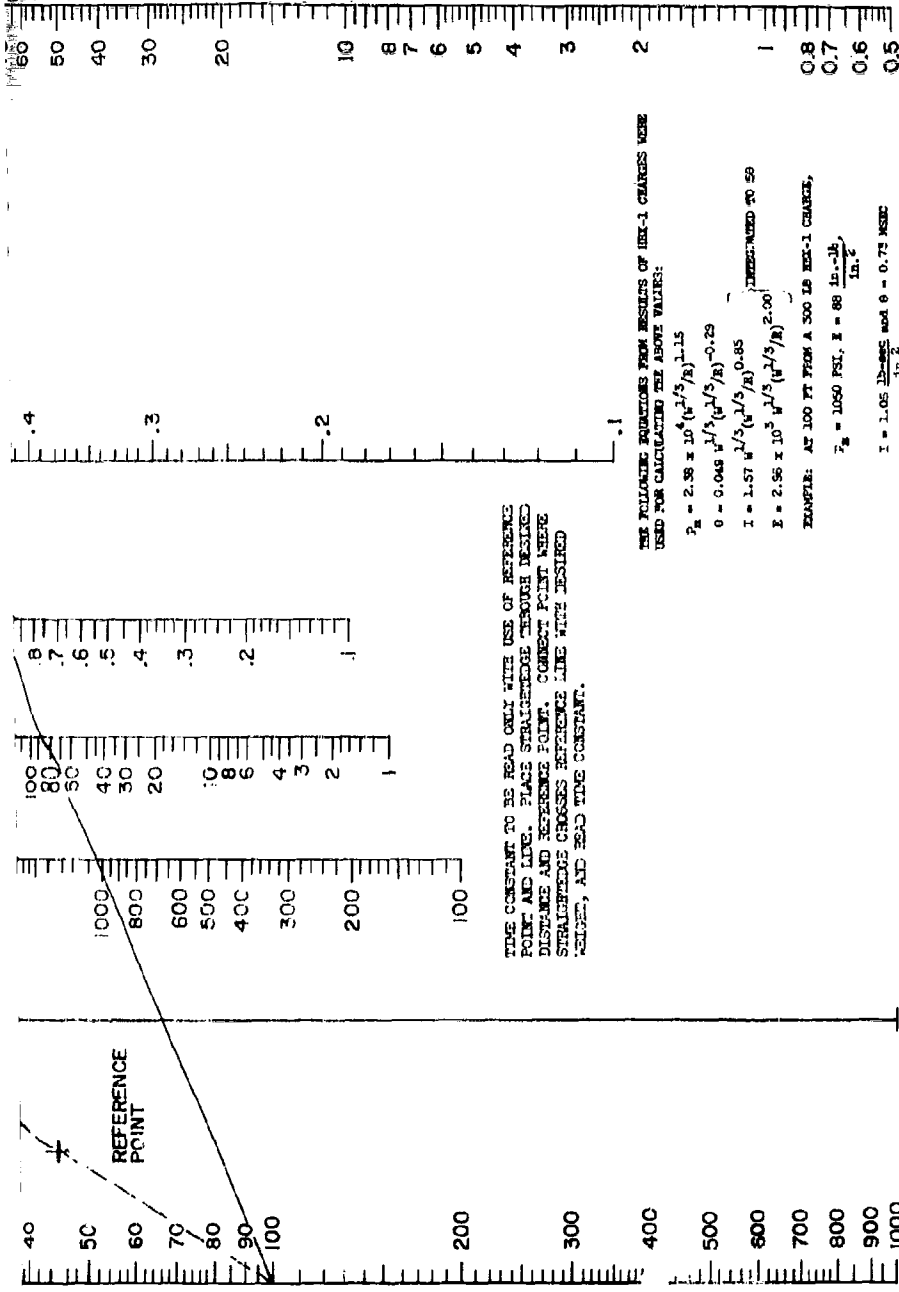
FIG. 5 COMPARISON OF REVISED AND NAVORD 2986 PENTOLITE SIMILITUDE EQUATIONS -  $P_m$  AND  $I/W^{1/3}$

FIG. 6 COMPARISON OF REVISED AND NAVORD 2986 PENTOLITE SIMILITUDE EQUATIONS -  $E/W^{1/3}$  AND  $\theta/W^{1/3}$



TIME CONSTANT TO BE READ ONLY WITH USE OF REFERENCE



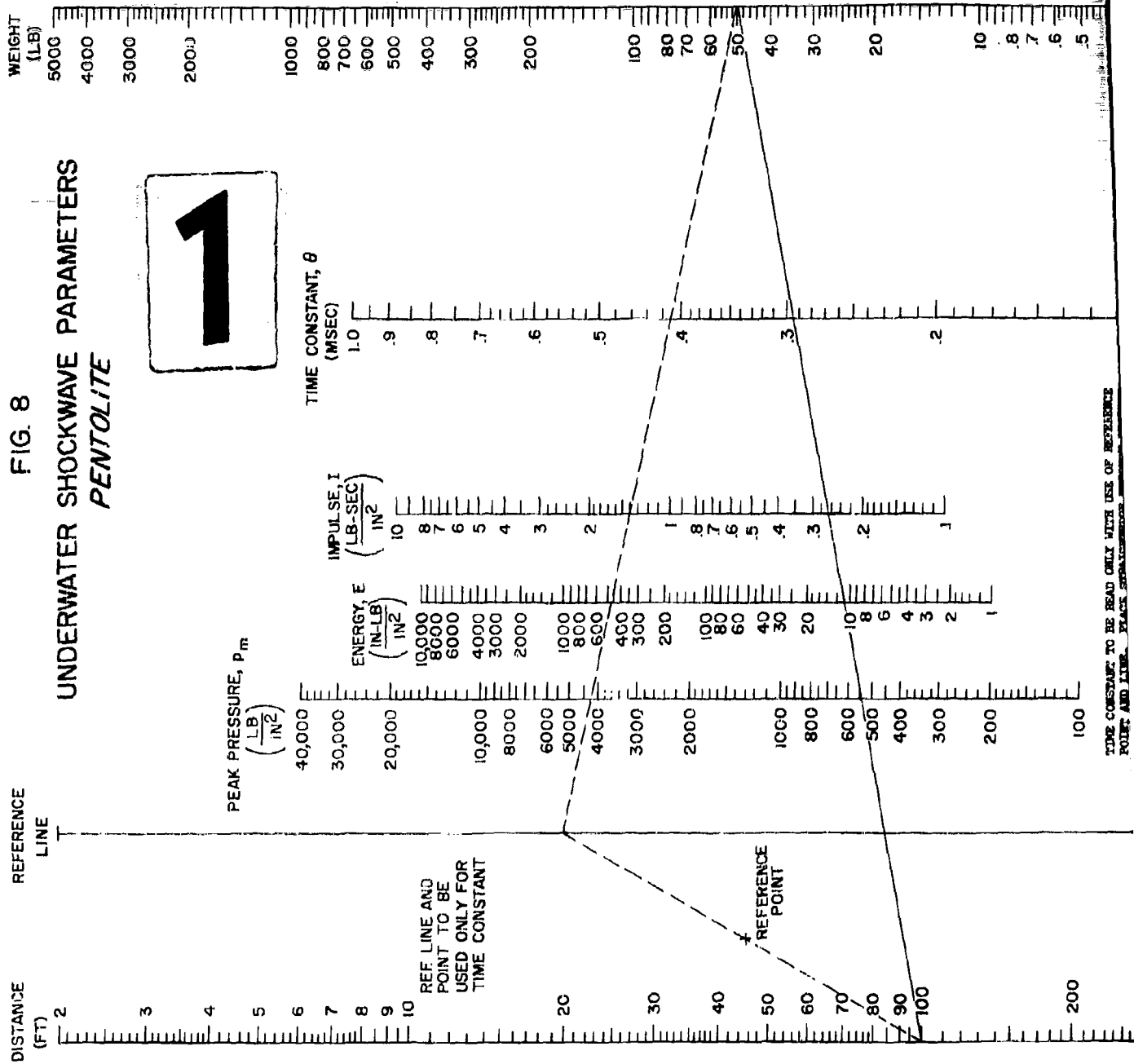


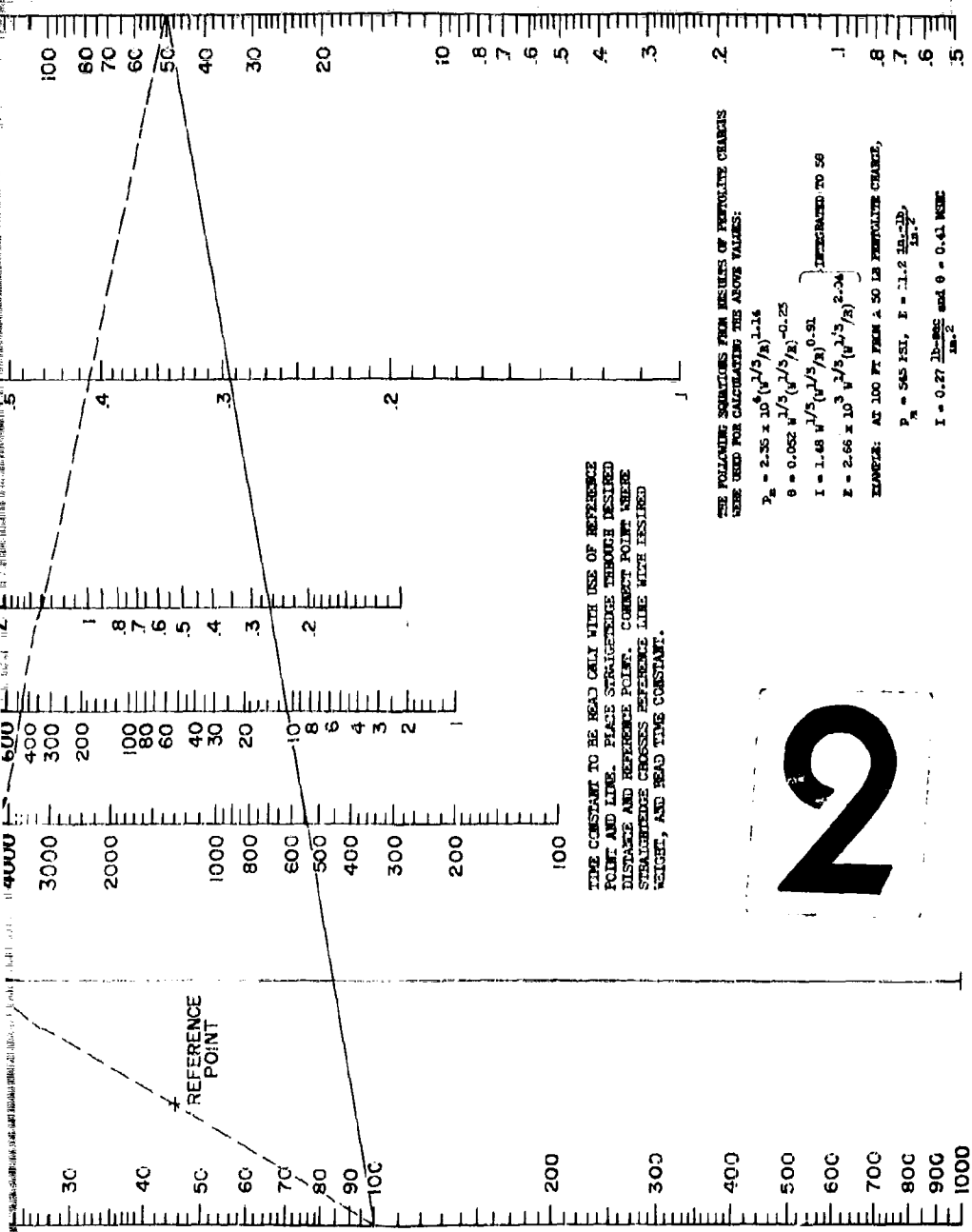
THE NOMOGRAPH YIELDS  $p_m$ , THE PEAK PRESSURE,  $\theta$ , THE TIME CONSTANT (i.e., THE TIME AT WHICH THE PRESSURE HAS DECAYED TO  $p_m/e$ ),  $I$ , THE POSITIVE IMPULSE, AND  $E$ , THE ENERGY, OF AN UNDERWATER SHOCKWAVE. THE SCALES CORRESPOND TO EMPIRICAL EQUATIONS, SHOWN ON THE NOMOGRAPH, WHICH WERE OBTAINED FROM MEASUREMENTS OF SQUAT CYLINDRICAL OR SPHERICAL CHARGES WEIGHING 1, 10, 30, 46, 50 AND 80 LBS.

THE SHOCKWAVE PRESSURE-TIME CURVE IS ESSENTIALLY AN EXPONENTIAL OF THE FORM  $p = p_m e^{-t/\theta}$  AT LEAST UNTIL A TIME  $t < \theta$ , BUT AT LATER TIMES THE PRESSURES DECREASE AT A RATE SLOWER THAN EXPONENTIAL. CONSEQUENTLY, IT IS NECESSARY TO MEASURE IMPULSE AND ENERGY TO SOME CHOSEN TIME IN ORDER TO OBTAIN A COMPARABLE VALUE; THE TIME LIMIT USED HERE IS  $5\theta$ . THE VALUES SHOWN FOR  $I$  ( $5\theta$ ) SHOULD BE INCREASED ABOUT 8% FOR A LIMIT OF  $6.7\theta$ , AND ABOUT 20% FOR A LIMIT OF  $10\theta$ . THE VALUES OF  $E$  ( $5\theta$ ) SHOWN HERE SHOULD BE INCREASED BY ABOUT 2% FOR A LIMIT OF  $6.7\theta$  AND ABOUT 4% FOR A LIMIT OF  $10\theta$ .

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TIME CONSTANT TO BE READ ONLY WITH USE OF REFERENCE POINT AND LINE. PLACE STRAIGHTEDGE THROUGH DESIRED DISTANCE AND REFERENCE POINT. CORRECT POINT MARKS STRAIGHTEDGE CROSSERS REFERENCE LINE WITH DESIRED WEIGHT, AND READ TIME CONSTANT.

THE FOLLOWING SCALINGS FROM RESULTS OF PROPAGATE CHARGES WERE USED FOR CALCULATING THE ABOVE VALUES:

$$P_m = 2.35 \times 10^4 (W^{1/3}/R)^{1.16}$$

$$\theta = 0.052 W^{1/3} (R^{1/3}/R)^{-0.25}$$

$$I = 1.48 W^{1/3} (R^{1/3}/R)^{0.51}$$

$$Z = 2.66 \times 10^3 W^{1/3} (R^{1/3}/R)^{2.24}$$

EXAMPLES: AT 100 FT FROM A 50 LB PERFORATE CHARGE,  
 $P_m = 545 \text{ PSI}, \theta = 1.12 \text{ MS}^{-1/2}$   
 $I = 0.27 \text{ MS}^{-1/2} \text{ and } Z = 0.41 \text{ MS}^{-1/2}$

THE NOMOGRAPH YIELDS  $P_m$ , THE PEAK PRESSURE,  $\theta$ , THE TIME CONSTANT (i.e., THE TIME AT WHICH THE PRESSURE HAS DECAYED TO  $P_m/e$ ),  $I$ , THE POSITIVE IMPULSE, AND  $Z$ , THE ENERGY OF AN UNDERWATER SHOCKWAVE. THE SCALES CORRESPOND TO EMPIRICAL EQUATIONS, SHOWN ON THE NOMOGRAPH, WHICH WERE OBTAINED FROM MEASUREMENTS OF SQUAT CYLINDRICAL OR SPHERICAL CHARGES WEIGHING  $\frac{1}{2}$ , 1, 2, 44, 51, AND 80 LBS.

THE SHOCKWAVE PRESSURE-TIME CURVE IS ESSENTIALLY AN EXPONENTIAL OF THE FORM  $p = P_m e^{-t/\theta}$  AT LEAST UNTIL A TIME  $t < \theta$ , BUT AT LATER TIMES THE PRESSURES DECREASE AT A RATE SLOWER THAN EXPONENTIAL. CONSEQUENTLY, IT IS NECESSARY TO MEASURE IMPULSE AND ENERGY TO SOME CHOSEN TIME IN ORDER TO OBTAIN A COMPARABLE VALUE; THE TIME LIMIT USED HERE IS  $5\theta$ . THE VALUES SHOWN FOR  $I$  (50) SHOULD BE INCREASED ABOUT 8% FOR A LIMIT OF  $6.7\theta$ , AND ABOUT 20% FOR A LIMIT OF  $10\theta$ . THE VALUES OF  $Z$  (50) SHOWN HERE SHOULD BE INCREASED BY ABOUT 2% FOR A LIMIT OF  $6.7\theta$  AND ABOUT 4% FOR A LIMIT OF  $10\theta$ .

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REVISED SIMILITUDE EQUATIONS FOR THE UNDER-  
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charts, tables. Project ROME-3-E-002/2121/  
FO08-10-004.  
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Equations represent an average and so when  
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Nomographs for obtaining shockwave parameters  
are included.

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Pentolites  
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II. Thiel,  
Mitchell A.  
III. Project

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