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Compressible Numerical Calculations of Underwater Detonations

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by

Charles L. Mader

COMPRESSIBLE NUMERICAL CALCULATIONS OF UNDERWATER DETONATIONS

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ABSTRACT

The detonation of a centrally initiated tetryl sphere in water at hydrostatic pressures of 10 to 4600 bars has been calculated by using the Becker-Kistiakowsky-Wilson equation of state for tetryl, a realistic treatment of the diverging detonation, and the SIN one-dimensional Lagrangian compressible flow hydrodynamic code. The interaction of the detonation products and the water is followed for at least one complete oscillation for each hydrostatic pressure studied. The calculated results agree with the experimentally observed interface position and water shock pressure and the position as a function of time.

I. INTRODUCTION

The prediction of water waves generated by large-yield underwater explosions has been based on extrapolation of empirical correlations of small-yield experimental data. The accuracy of such predictions is unknown, consequently, there is need for a detailed description of the mechanism by which waves are generated by underwater explosions. As a first step, the details of the energy partition between the detonation products and the water requires accurate calculation. Therefore, this investigation was made to determine if our best equation of state for explosives (Becker-Kistiakowsky-Wilson) and our most realistic method of describing a diverging detonation were adequate to reproduce the observed short- and long-time behavior of an underwater detonation by using a high-resolution, one-dimensional Lagrangian reactive hydrodynamic code such as SIN.

II. EQUATIONS OF STATE

The Becker-Kistiakowsky-Wilson (BKW) equation of state was used to describe the equation of state of tetryl from 0.5 to 5 x 10^{-7} Mbar. The equation-of-state parameters were the RDX parameters described in Ref. 1. The equation of state used for water was a linear shock velocity-particle velocity fit to the experimental data of Rice and Walsh[2] for the low-pressure, single-shock Hugoniot and a Grüneisen equation of state for state values off the Hugoniot. The Hugoniot temperatures were computed by using the technique of Walsh and Christian.[3] The resulting treatment is known as the HOM equation of state and is used in the SIN code.[4] The equation-of-state constants are given in Table I.

III. DIVERGENT DETONATIONS

As discussed previously,[5] a theoretical treatment of a spherically expanding detonation wave does not exist. The Taylor self-similar solution for divergent detonations has been widely used for lack of a better treatment; however, Courant and Friedrichs[6] show that it is not correct. The Taylor self-similar solution does not permit the pressure at the end of the reaction zone to change with the divergence of the flow.

Although a theoretical treatment does not exist and we cannot follow the calculation with a resolved reaction zone for a long distance,[7] we can perform one-dimensional numerical hydrodynamic calculations by using Arrhenius kinetics and unresolved reaction zones. The important features of the flow do not depend upon the mesh size or detailed kinet-

TABLE I

BRW EQUATION-OF-STATE CONSTANTS FOR TETRYL

A	-3.63800897230+00	R	-4.24673177898-01
B	-2.45393338654+00	S	+8.78387835435-02
C	+3.10500324662-01	T	-9.19711030854-03
D	-3.05988910545-02	U	+8.51766433852-05
E	+8.47652818961-04	C'_v	+0.5
K	-1.61514480846+00	Z	+0.1
L	+4.45469837845-01	ρ_o	1.70 g/cm^3
M	+5.81234373927-02	P_{CJ}	0.2515 Mbar
N	+3.69359509121-03	D	0.7629 cm/μsec
O	+8.90241616462-05	T	2917^{o}K
Q	+7.55699503132+00		

HOM EQUATION-OF-STATE CONSTANTS FOR WATER

C	+1.483-01	J_s	-4.77056213831+00
S	+2.0+00	γ_s	+1.0+00
F_s	+5.69548170482+00	C_v	+1.0+00
G_s	-4.17083639420-01	V_o	+1.0+00
H_s	-2.95746672807+00	α	+1.0-04
I_s	-1.04778472547+01		

The symbols used for the HOM equation-of-state constants are identical to those of Ref. 4.

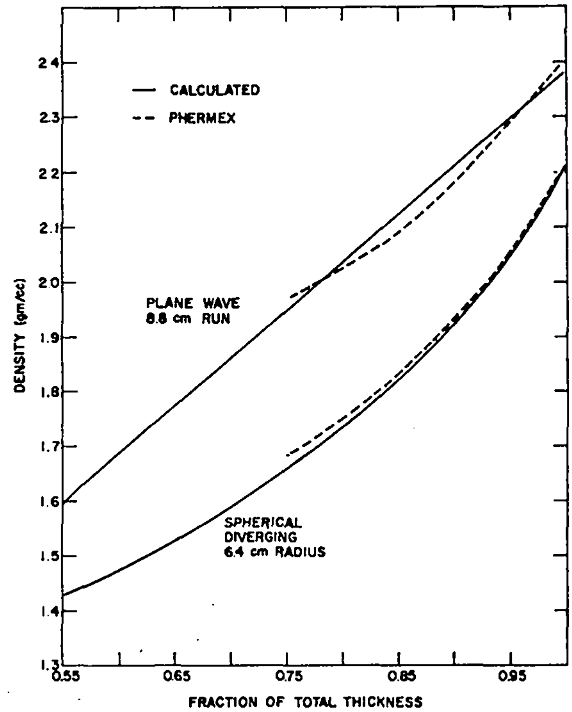

Fig. 1. The calculated and PHERMEX experimental Taylor wave densities of 1.73 g/cm^3 Composition B-3 explosive.

ics. For an overdriven detonation, the pressure decreases until it is considerably less than the Chapman-Jouget (C-J) value and then slowly increases toward the C-J value. For an underdriven detonation, the pressure slowly increases toward the C-J value.

Venable[8] has taken PHERMEX radiographs of the detonation wave of Composition B-3 by using embedded tantalum foils to determine the particle velocity and density throughout the Taylor wave in plane and spherically diverging geometry. The experimental slab effective C-J density is 2.4 ± .05 g/cm^3 and the experimental diverging peak density is 2.2 ± .05 g/cm^3. By using a gamma law or BKW equation of state, excellent agreement is obtained between the calculated and experimental Taylor wave densities for the front quarter of the wave as shown in Fig. 1. This is evidence that the Taylor self-similar solution is incorrect and that the calculated flow in diverging geometry is adequately reproducing the actual flow.

Another divergent system for which experimental data are available is a 4.5-in.-diam, 1.69 g/cm^3 9205 sphere detonated from the center by a 0.25-in.-diam detonator surrounded by 13 cm of water. This system has been studied by Hantel and Davis.[9] The BKW C-J pressure for 9205 is 280 kbar and the calculated peak detonation pressure of the 9205 is 230 kbar. The calculated and experimental positions of the shock front in the water as a function of time are shown in Fig. 2. They agree to within the error of the experimental data.

A theoretical treatment of the diverging detonation does not exist; however, we have used a computational model that appears to be realistic because it reproduces the available one-dimensional, divergent flow experimental data.

IV. THE NUMERICAL METHOD

The SIN one-dimensional reactive Lagrangian hydrodynamic code[4] was used to study the flow resulting from the detonation of a 3.27-cm radius sphere of tetryl in water at various initial pressures and densities. To conserve computer time, only 1000 cells were used in the calculation with the explosive initially resolved to 0.1 cm and the first 10 cm of water resolved to 0.25 cm. For the low initial-pressure calculations, the water cell

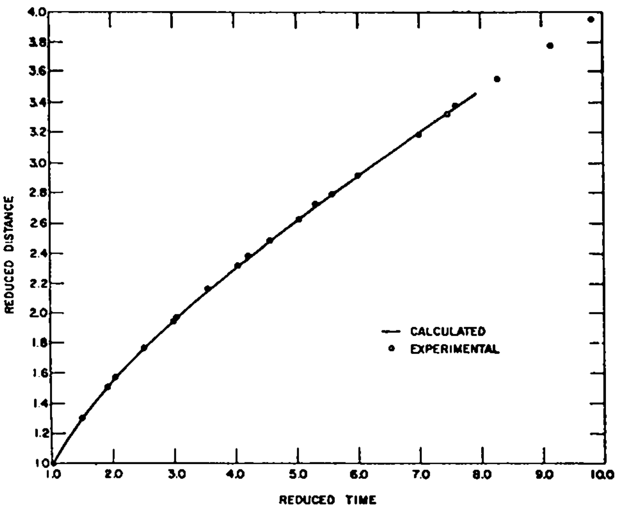

Fig. 2. The calculated and experimental position of the shock front in water as a function of time for a 4.5-in. sphere of 9205 in water. The reduced units are those used by Hantel and Davis[9] where reduced time is $(t_o + a/D)/(a/D)$, reduced distance is $(R_o + a)/a$, t_o is time from breakout, a is sphere radius, D is detonation velocity, and R_o is distance of shock front from sphere surface.

width was then increased to allow sufficient distance to follow the water shock during the time of interest. This resolution was adequate to assure that the important features of the flow were mesh and viscosity independent.

This technique required smaller time steps and more computer time than would be necessary if one of the new implicit compressible schemes such as ICE[10] were used. After the implicit schemes have been better developed and have been tested, future studies of this type should give careful consideration to the use of such techniques.

V. THE RESULTS

Numerical calculations of underwater detonations have been performed by many investigators, and the work of Sternberg and Walker[11] is an outstanding example of work in progress during recent years. The details of the equation of state of the explosive, the treatment of divergent detonations, and the calculation to bubble collapse for low hydrostatic pressures are the major differences between this study and those that have preceded it. Our results differ in some details (for example, the initial shock pressure in the water is lower); however, the main features of the flow are similar to those reported by Sternberg and Walker.

We chose to study the explosive system of a 0.55-pound sphere of tetryl at various depths because the system was experimentally studied in detail and described by Cole.[12] The BKW C-J pressure for 1.70 g/cm^3 tetryl is 251 kbar and the calculated peak detonation pressure of a 3.27 cm radius tetryl sphere is 200 kbar. The results of our study are summarized in Table II.

TABLE II

SUMMARY

No.	Hydrostatic Pressure (bars)	Depth (ft)	Period (μsec)	Maximum Radius (cm)
1	4660	~156,000	200	6.3
2	462	~ 15,500	1225	12.5
3	74.6	~ 2,500	5400	23.5
4	9.91	~ 300	25,500	46.5

The calculated pressure-time histories and bubble radius-time histories for 3.27-cm radius tetryl spheres in water with hydrostatic pressures of 4660, 462, 74.6, and 9.91 bars are shown in Figs. 3 through 10. The experimental bubble radius-time profile as reported by Cole[12] is also shown in Fig. 10. The calculated results appear to reproduce the experimental observations. Figure 11 shows the calculated and experimental bubble periods as a function of water depth and the agreement is satisfactory.

Figures 12 and 13 show early time profiles for several of the cases studied. It is interesting to note that higher hydrostatic pressure systems have nearly identical pressure-time profiles as the lower hydrostatic pressure systems until the tetryl-water interface pressure drops to near the hydrostatic pressure. The pressure gradient behind the water shock becomes less steep for the higher hydrostatic pressure systems and determines when the bubble will collapse. At lower hydrostatic pressures, many reverberations occur during expansion and collapse of the bubble and the pressure-time and pressure-distance profiles become very complicated.

As described by Pritchett[13] and others[12] the simple incompressible model predicts that the maximum bubble radius is inversely proportional to the hydrostatic pressure to 1/3 power and the period is

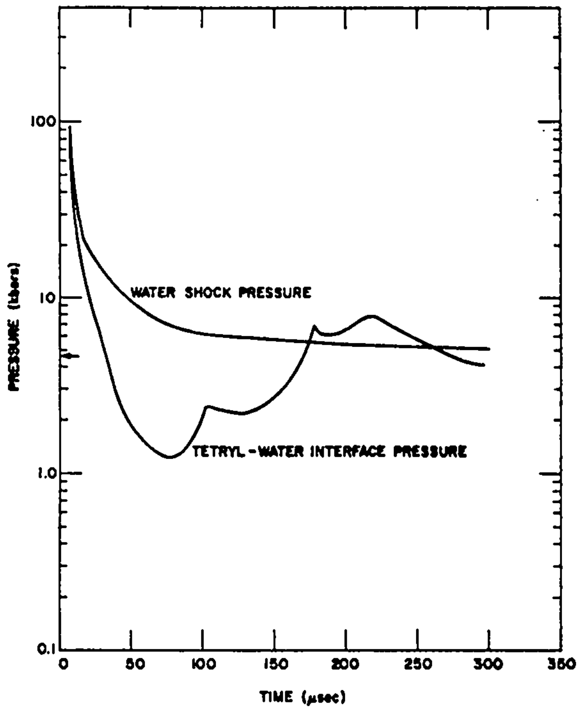

Fig. 3. The water shock and tetryl-water interface pressure as a function of time for a 3.27-cm radius tetryl sphere in water at 4660 bars.

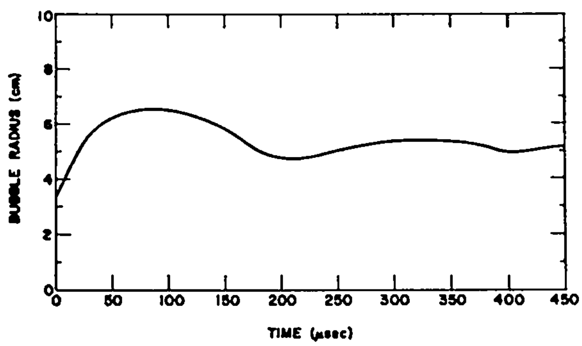

Fig. 4. The bubble radius as a function of time for a 3.27-cm radius tetryl sphere in water at 4660 bars.

inversely proportional to the hydrostatic pressure to 5/6 power. Our calculated results are in good agreement with these predictions for the maximum bubble radius, but are in poorer agreement for the periods as shown in the following table. The calculated period is inversely proportional to the hydrostatic pressure to the 0.877 power.

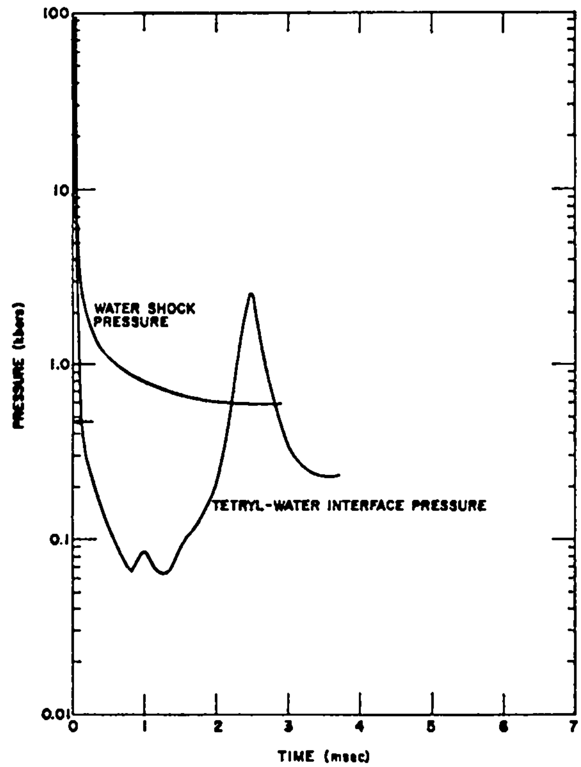

Fig. 5. The water shock and tetryl-water interface pressure as a function of time for a 3.27-cm radius tetryl sphere in water at 462 bars.

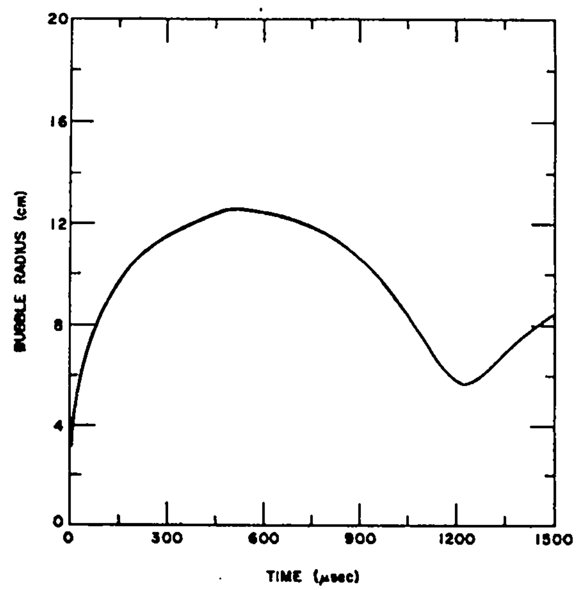

Fig. 6. The bubble radius as a function of time for a 3.27-cm radius tetryl sphere in water at 462 bars.

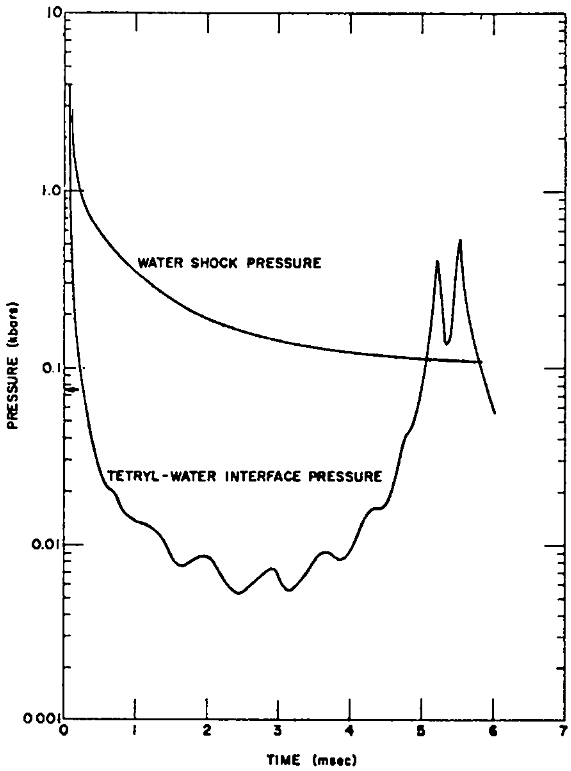

Fig. 7. The water shock and tetryl-water interface pressure as a function of time for a 3.27-cm radius tetryl sphere in water at 74.6 bars.

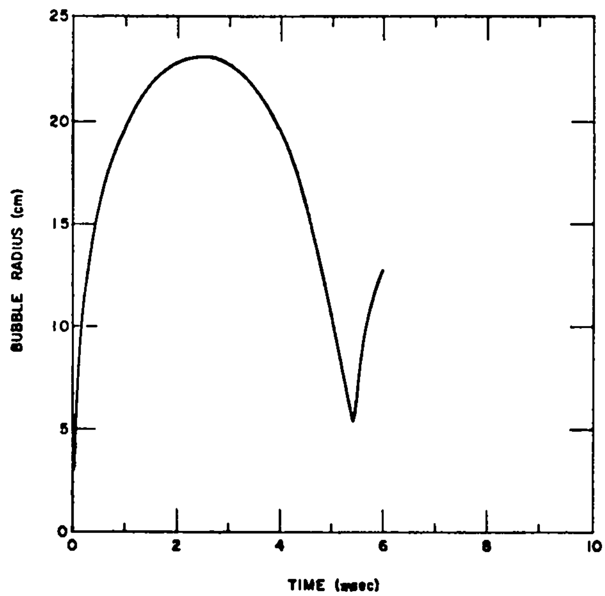

Fig. 8. The bubble radius as a function of time for a 3.27-cm radius tetryl sphere in water at 74.6 bars.

Calculations	Ratio of Max Radii	Ratio $P^{1/3}$	Ratio of Periods	Ratio $P^{5/6}$
4/1	7.38	7.78	127.5	168.6
4/2	3.72	3.60	20.8	24.6
4/3	1.98	1.96	4.7	5.4
3/2	1.88	1.84	4.4	4.6
2/1	3.73	3.97	27.0	31.3
2/1	1.98	2.16	6.1	6.8

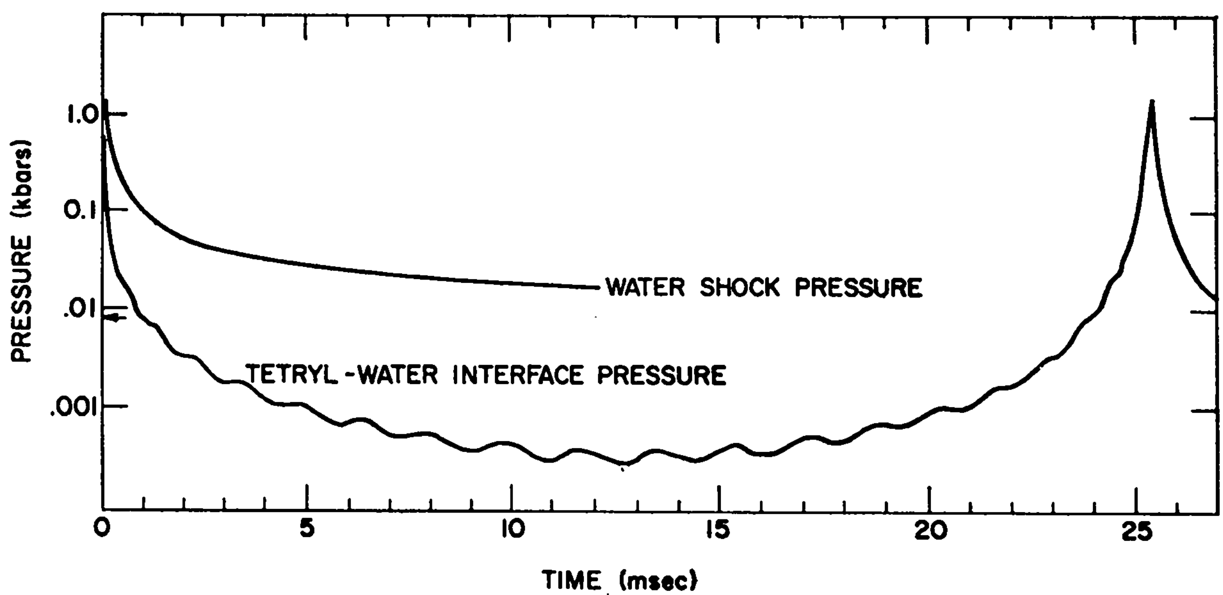

Fig. 9. The water shock and tetryl-water interface pressure as a function of time for a 3.27-cm radius tetryl sphere in water at 9.91 bars.

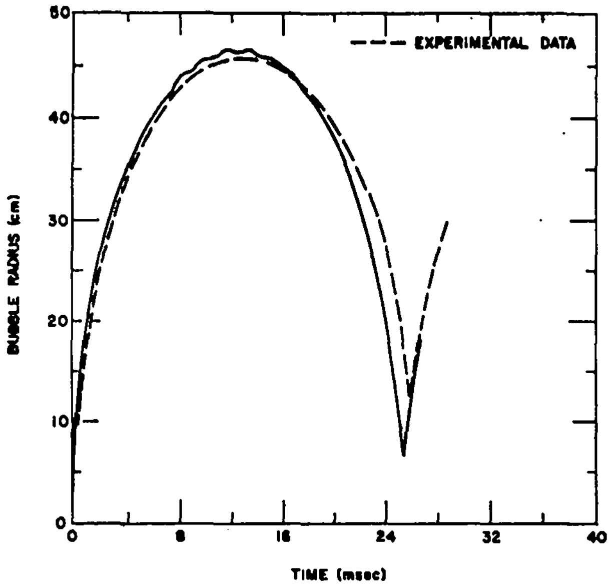

Fig. 10. The bubble radius as a function of time for a 3.27-cm radius tetryl sphere in water at 9.91 bars. The experimental data are also shown.

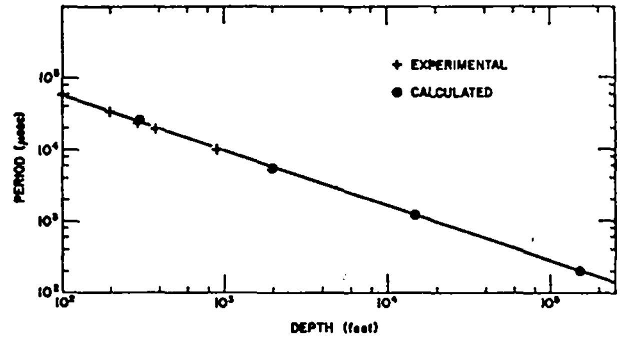

Fig. 11. The calculated and experimental bubble periods as a function of water depth.

VI. CONCLUSIONS

The agreement between the observed long-time behavior of an underwater detonation and the detailed one-dimensional compressible hydrodynamic calculations using our best explosive equations of state and descriptions of the diverging detonation suggests that the calculated energy partition between the detonation products and the water is sufficiently accurate to be used in future multidimensional studies of wave generation mechanisms of underwater explosives.

Although such agreement is necessary, it is, of course, not sufficient to eliminate the possibility that the calculated energy partition is incorrect.

An extensive study of detonations in divergent geometry with resolved reaction zones is in progress and should furnish us with a better theoretical understanding of diverging detonations.

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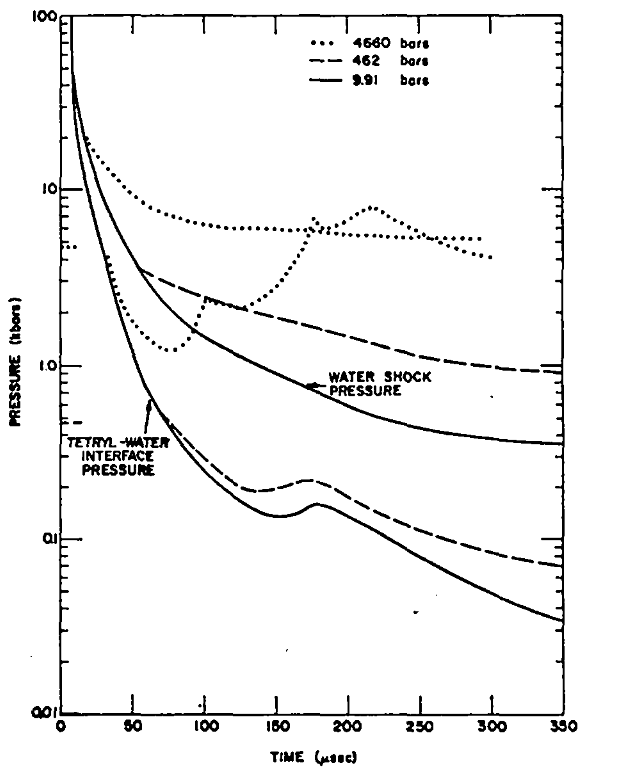

Fig. 12. The water shock and tetryl-water interface pressure as a function of time for early times.

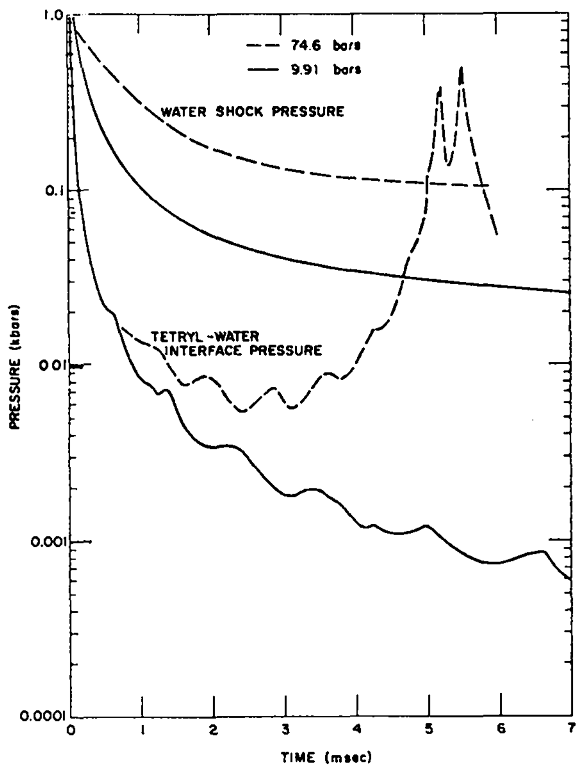

Fig. 13. The water shock and tetryl-water interface pressure as a function of time at early times.

Gaylord Miller of ESSA Institute for Oceanography, Julius Enig and W. A. Walker of U. S. Naval Ordnance Laboratory, Bernard Le Mehaute of Tetra Tech, Inc., and John Pritchett of Information Research Associates, Inc.

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