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NUMERICAL SIMULATION OF THE COLLAPSE
OF AN UNDERWATER EXPLOSION BUBBLE

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- a. Papers submitted to refereed journals (and not yet published):
None
- b. Papers published in refereed journals:
none
- c. Books (and sections thereof) submitted for publication:
none
- d. Books (and sections thereof) published:
none
- e. Patents filed:
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- f. Patents granted:
none
- g. Invited presentations at topical or scientific/technical society conferences:
none
- h. Contributed presentation at topical or scientific/technical society conferences:
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- i. Honors/Awards/Prizes:
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Interim Report on
Numerical Simulation of the Collapse
of an Underwater Explosion Bubble

ONR Contract N00014-87-K-0428

Purpose: The goal of this project is to demonstrate the usefulness of front tracking (J. Glimm, et. al., Courant Institute, NYU) as a tool to study the fully compressible axially symmetric expansion and collapse of an underwater explosion bubble in two spatial dimensions. In the pilot project supported by this contract a one-dimensional version of the front tracking code is being implemented to compute spherically symmetric oscillations. The one dimensional version will be used to gain expertise in the problem, to pinpoint areas of difficulty, and to determine the feasibility of using the two dimensional front tracking method for this problem.

Status to date and conclusions: We have validated a one dimensional, tracked random choice code adapted for this pilot project on published computational and experimental results. These validation studies are discussed in the Appendix. As a result of these validation studies, we have identified problem areas that exist. Identified problem areas include the necessity for realistic equations of state for the explosion products, implementation of effective boundary conditions that would take into account the progress of the primary shock wave into the water without the necessity of keeping it within the computational domain, improved treatment of the divergence at the bubble center by analytic means, and correct initiation of the explosion remnants.

We have formulated plans for overcoming each of these problem areas. These are discussed in the next section of this report. Finally we conclude that the two dimensional computation of axially-symmetric bubble oscillation is easily possible for deep water (i.e. 4.66 kbar to 426 bar depths) explosions. However simulation of shallower depths (i.e. 74.6 bars) will require some combination of the

improvements specified below to achieve practical computational times.

Future improvements: The comparisons with the SIN calculations of C. Mader reveal that the use of a polytropic equation of state for the gaseous explosion products is inadequate. After discussions with C. Mader, we are currently implementing the HOM equation of state for the reactive products. Two implementations are planned. The first will use the HOM equation of state to generate data tables in the format of the SESAME material library. These data tables can then be used by the Riemann solver developed by J. Scheuerman of the Courant Institute. This will allow random choice and front tracking calculations. The second approach will be the development of an analytic Riemann problem solver specific to the HOM equation of state. This will provide a more robust and faster running code.

The correct simulation of the boundary conditions of the oscillating bubble problem requires that the effects of the primary shock wave traveling through the water be taken into account until it is reduced to negligible strength. In all published compressible computations to date, this requirement has necessitated keeping the primary shock wave within the computational domain until its strength is negligible, at which time it can be terminated at a boundary that models far field ambient water conditions. For shallower underwater explosions, this distance can be hundreds of bubble radii. Most of this distance, from the maximum bubble radius to the far ranging primary shock is computationally wasteful and would best be replaced by effective boundary conditions. We plan to remove the necessity of tracking the primary shock over large distances by using the ideas of T. Hagstrom and others [2] to achieve the required effective boundary conditions.

Our comparisons with the published work of Saito and Glass [4] have revealed the inadequacies of the numerical cutoff used at the center of the bubble (radius = 0), which is the common numerical implementation to avoid the divergence of the Euler equations in spherical coordinates. The treatment at the origin, for spherically and cylindrically symmetric calculations, affects the dynamics of the calculation, especially if waves converging into the origin produce strong reflected signals, as happens in these bubble explosion problems. We plan to investigate the implementation of an analytic treatment of the solution near the origin along the line of Noh's work.

Finally, correct initiation of the explosive remnants appears important in order to achieve the final level of agreement between calculations and experiments that is desirable. This requires modeling the reactive phase of the explosion. We plan to implement one of the models discussed by C. Mader [3].

Appendix

Validation with current published results: As a first step in validating the tracked random choice code, we have compared results with two other published one-dimensional, untracked random choice calculations. The first of these is a calculation by J. Flores and M. Holt [1] of an underwater explosion at a depth of one foot. The calculation is fully compressible, using the inviscid Euler equations modeling the gas bubble and the water. The gas bubble is modeled with a polytropic gas equation of state, the water with the separable energy, Tait equation of state. The numerical method is random choice combined with Sod's operator splitting technique to include the source terms of spherical geometry. The initial bubble radius is 1/3 foot and the calculation is followed until the spherical primary shock wave has traveled 1 foot, that is until the shock wave reaches the water surface.

We performed the same untracked calculation, using instead a stiffened polytropic equation of state for the water. Thermodynamic profiles (pressure, density, velocity) produced by the two simulations show only small differences, attributable to the different equations of state for water. The comparisons are shown in Fig. 1.

A second comparison was made against the computation reported by T. Saito and I. Glass [4] who performed an untracked random choice calculation of the motion of a helium bubble in air at unit atmosphere pressure. Both the helium and air were treated as polytropic gases. The calculation follows the leading shock in the air until it has traveled five times the initial bubble radius, approximately the time required for one bubble oscillation. Results again agree very well when we use the same calculational scheme as Saito and Glass. The pressure comparisons are shown in Fig. 2. The Saito-Glass experiment is however less demanding than that of Flores-Holt as the sound speeds in air and helium are much more closely matched than those in gas and water.

Our investigations have revealed the importance of the cutoff at the center of the bubble (radius = 0), which is required to prevent numerical divergences, a point glossed over in the Saito-Glass report. It is known that the treatment at the origin, for spherically and cylindrically symmetric calculations, affects the dynamics of the calculation, especially if waves converging into the origin produce a strong reflected signal. In these bubble explosion problems, such a signal develops during the collapse phase. We have shown that the speed of the two important waves, the initial shock in the air and the helium-air interface (or, for the explosion underwater, the shock in the water, and the water-gas interface) is affected by these reflected waves. The smaller the cut-off, the slower the outgoing shock wave moves during the compressive phase. However, reducing the cut-off (by which we mean actually calculating closer to the origin) also causes a reduction in timestep size which greatly increases the computational time.

In a final set of validation studies we calculated the oscillation of a bubble caused by detonating 0.55 pounds of tetryl at three separate underwater depths. These were compared to calculations reported by C. Mader [3] using the SIN code. As the SIN calculations computed the detonation phase of the explosion, the initial data used by the random choice code had to be approximated from the explosion data. The initial data used are:

bubble radius	3.27 cm
bubble pressure	0.251 Mbar
bubble density	1.7 gm/cm ³
ratio of specific heats in bubble	2.93
ambient water pressure	74.6 bars, 462 bars, 4.66 kbars
ambient water density	1.0 gm/cm ³

In comparing the SIN calculations reported by Mader with the tracked random choice code results, two differences in the approximation methods that are likely to account for differences in the results should be noted. First, the SIN code uses a more realistic equation of state to model the explosive products, whereas the random choice computation models the explosive products as a gamma law gas. Second, the SIN code initiates a simulation by modeling the detonation phase, whereas the random choice method is initiated at the completion of detonation as a high-density, high-pressure, underwater gaseous sphere with velocity everywhere

specified as zero. This assumption is of course incorrect; by the time detonation is complete, velocities inside the gas sphere are nonzero. In addition, the random choice calculations assume complete combustion of the explosive, that is, that the initial bubble density is constant in the bubble and equal to that of undetonated tetryl. A realistic detonation model would compute a more accurate density profile for the explosive products. These two distinctions between SIN and the random choice code used here should account for most of the differences appearing in the results. In the next phase of the project, we plan to implement the HOM equation of state model for the gaseous explosive products either in table-lookup form or in analytic form. This upgrade should improve agreement with the SIN code, and with experimental results. At a still later stage of the project, a more realistic initiation will be introduced, perhaps by modeling detonation numerically.

Figure 3 compares plots of bubble radius as function of time for the SIN computations and the tracked random choice computations for tetryl detonated at 4.66 kbars ($\approx 156,000$ feet). The random choice bubble has a larger maximum radius and a shorter period of oscillation, but agreement with the SIN calculations at this depth is good. In particular, bubble oscillations are damped and equilibrium is reached after the same number of periods.

Figure 4 compares plots of primary shock pressures and gas-water interface pressures for tetryl detonated at 4.66 kbars. The minimum interface pressure calculated by the tracked random choice code is smaller than that of the SIN calculation, a result which is consistent with the bubble radius results. Pressures at the primary shock agree very well.

Figures 5 and 6 compare simulations for tetryl at 462 bars ($\approx 15,500$ feet). Figure 5 is a superposition of plots of bubble radius versus time. The bubble-radius profile calculated by the tracked random choice code has a greater maximum and shorter period than that of the SIN calculation. Agreement with the SIN code result is within 20%. Figure 6 compares plots of pressure at the primary shock and pressure at the gas-water interface. The pressure at the bubble-radius maximum computed by the tracked random choice code is very nearly an order of magnitude smaller than that computed by the SIN code, a consequence of modeling the explosion products as a gamma law gas.

Figures 7 and 8 are superpositions of plots of bubble radius versus time, primary shock pressure versus time, and gas-water interface pressure versus time for tetryl detonated at 74.6 bars ($\approx$ 2,500 feet). Figure 7 shows the bubble radius computed by the tracked random choice code has a smaller maximum radius and shorter period than the SIN code calculation. Figure 8 shows that the interface pressure calculated by the tracked random choice code is nearly two orders of magnitude smaller than that computed by the SIN code. Primary shock pressures agree until the pressure in the tracked random choice calculation suddenly decreases when the shock wave leaves the computational domain. (The boundary pressure is held at ambient value.) The smallness of the computational domain is the reason why the random choice solution underestimates maximum bubble radius while in previous cases it over estimated maximum bubble radius. This phenomenon has been observed in earlier test computations. The primary shock wave reaches the computational boundary before the bubble reaches its first minimum. Further, the difference between pressure behind the shock and the ambient water pressure is too large when the shock wave reaches the boundary.

References

1. J. Flores and M. Holt, "Glimm's Method Applied to Underwater Explosions," *J. Comp. Phys.*, vol. 44, pp. 377-387, 1981.
2. T. Hagstrom and S. I. Hariharan, "Accurate boundary conditions for exterior problems in gas dynamics," *SUNY, Stony Brook preprint*, 1987.
3. C. Mader, *Numerical Modeling of Detonation*, University of California Press, Berkeley, California, 1979.
4. T. Saito and I. I. Glass, "Application of random-choice method to problems in gasdynamics," *Prog. Aerospace Sci.*, vol. 21, pp. 201-247, 1984.

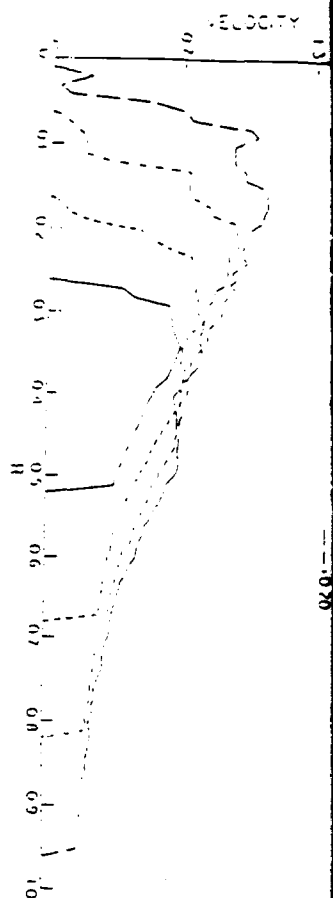
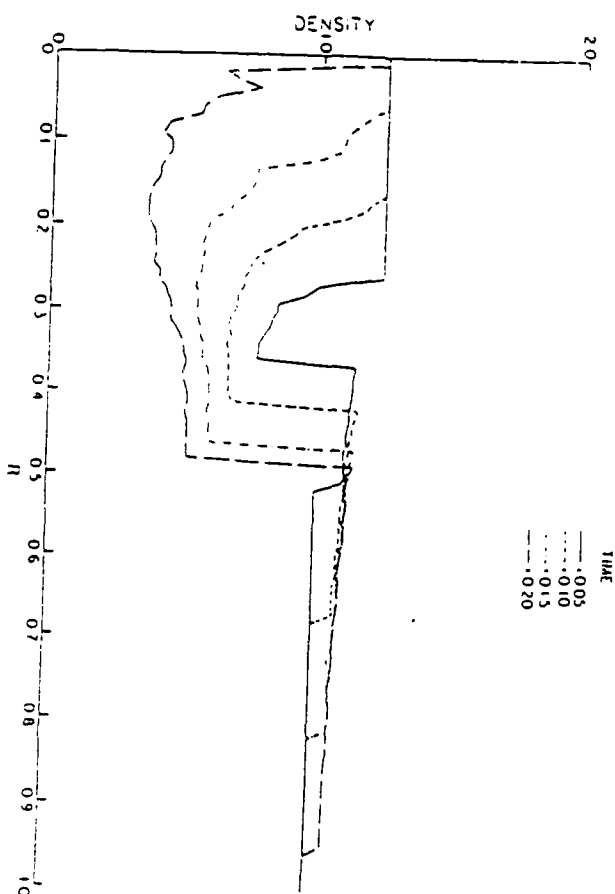


TABLE I
Values of Basic Parameters

Initial radius of gas sphere	1/3 ft
Depth of gas sphere center	1 ft
Initial pressure of explosion gas	9000 atm
Initial explosion gas temperature	2500°K
Specific heat ratio in explosion gas	1.4



(a)

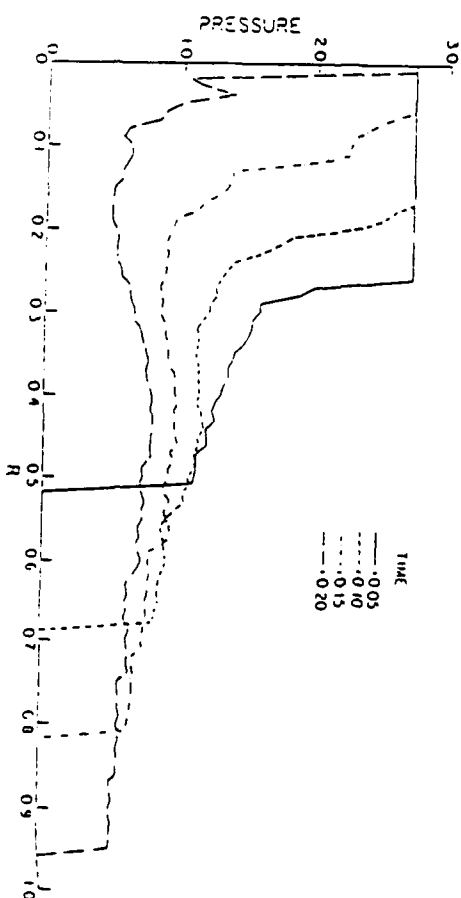
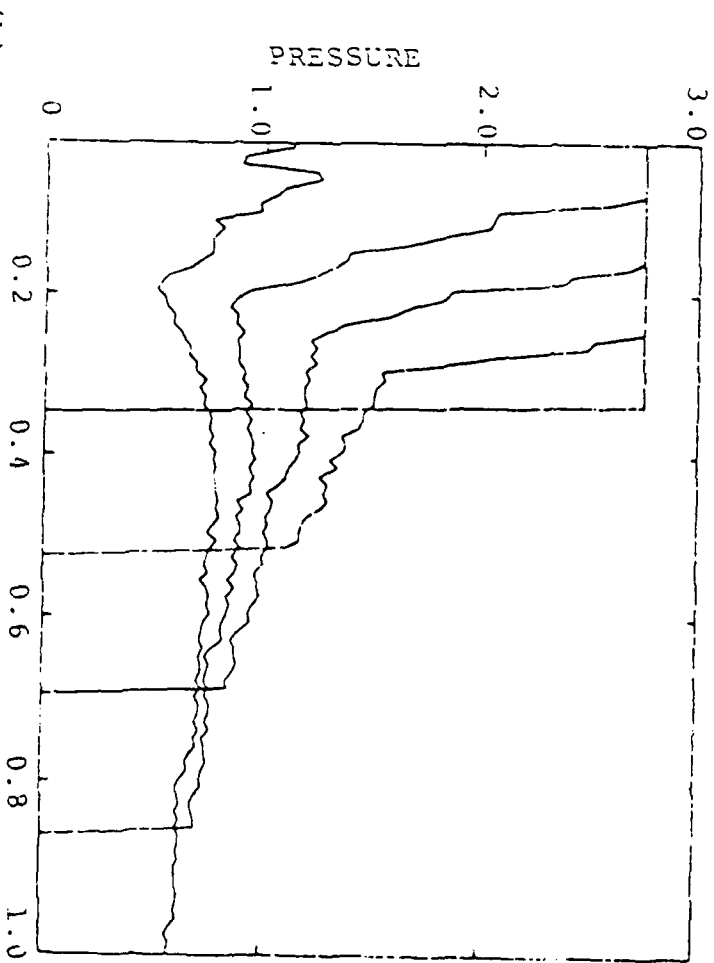
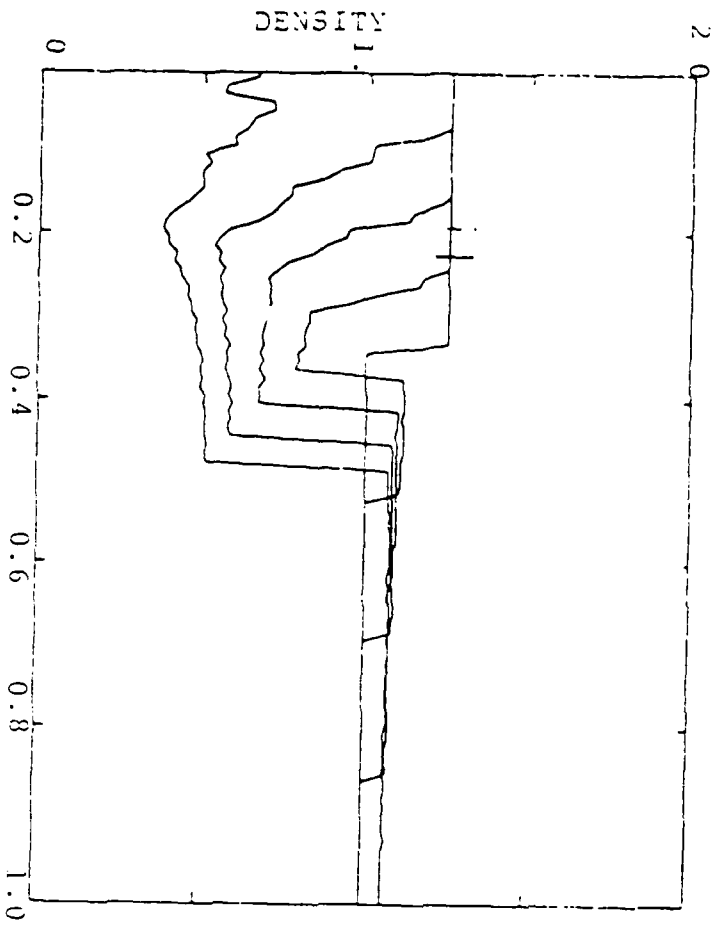
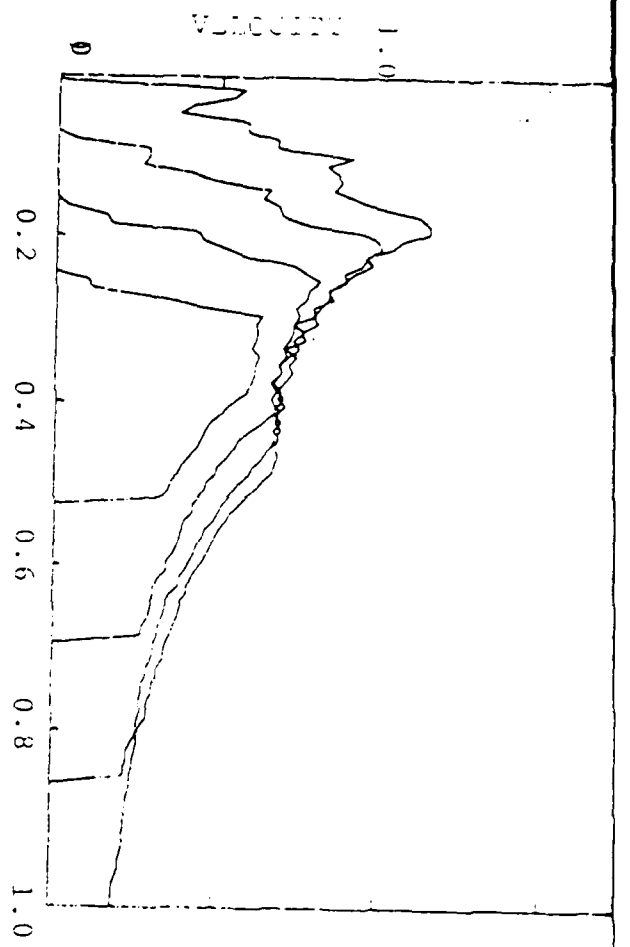
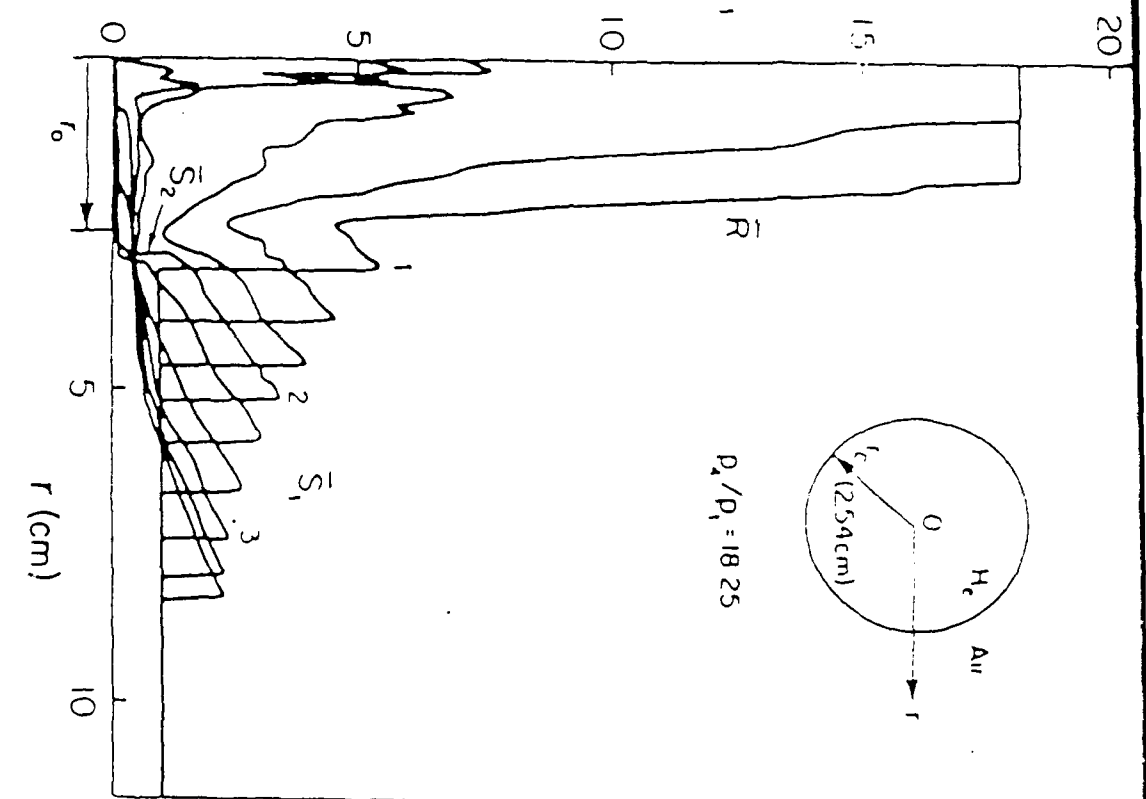


Figure 1. Comparison of the pressure, density and velocity profiles for the 1 foot depth explosion of (a) Flores and Holt (from J. Comp. Phys. 44, 337-387 (198.)) and (b) the random choice code for this project. Corresponding plot axes in (a) and (b) are in the same units, but the plots are not to the same scale.





(a)

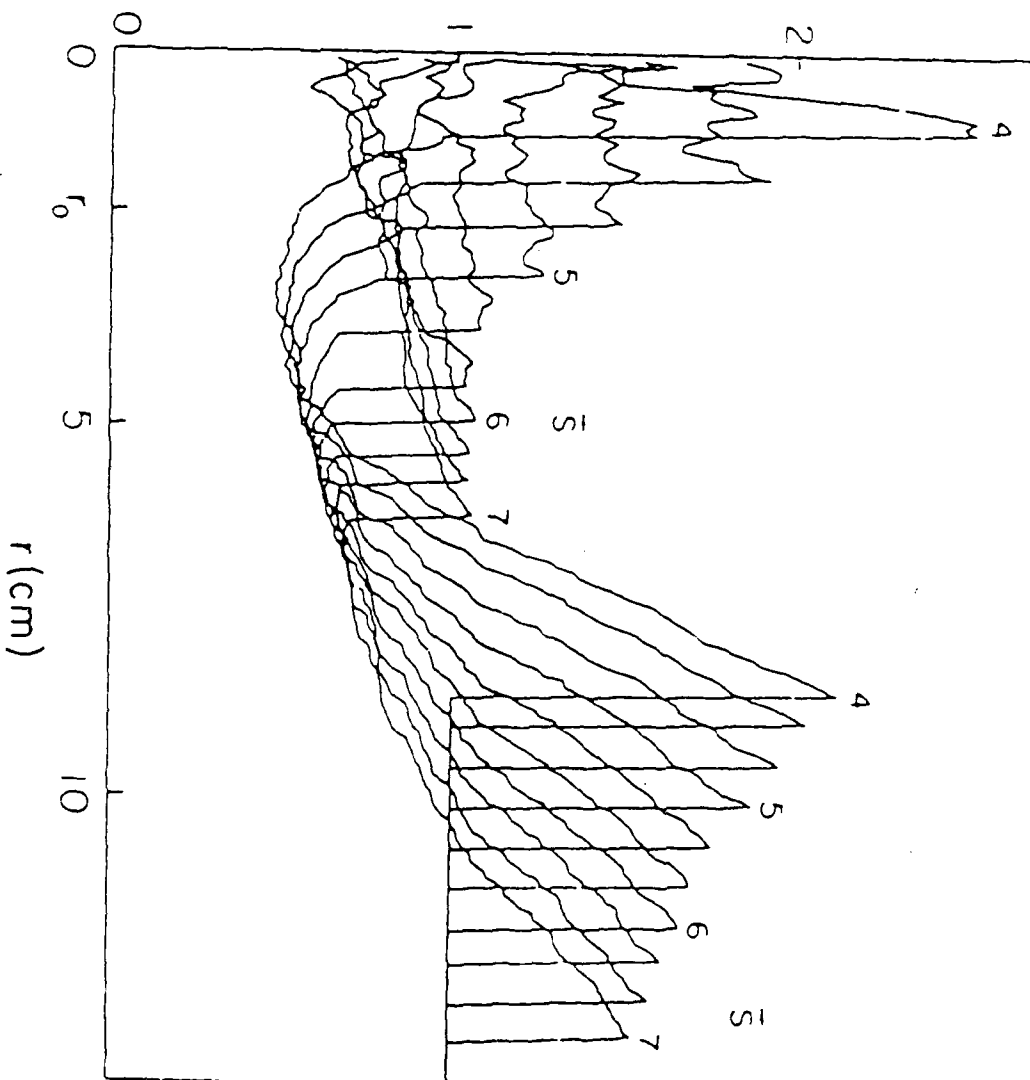
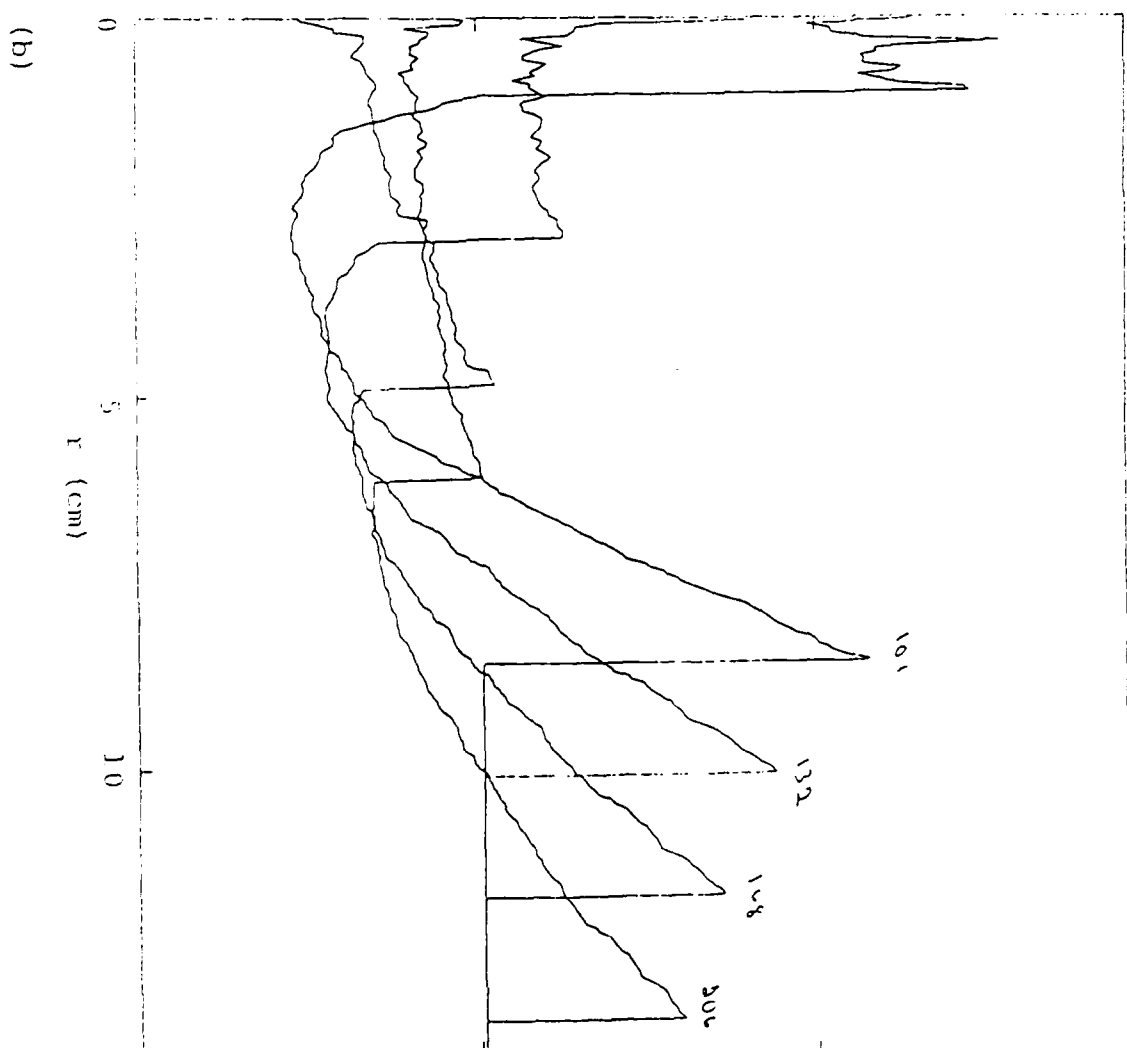
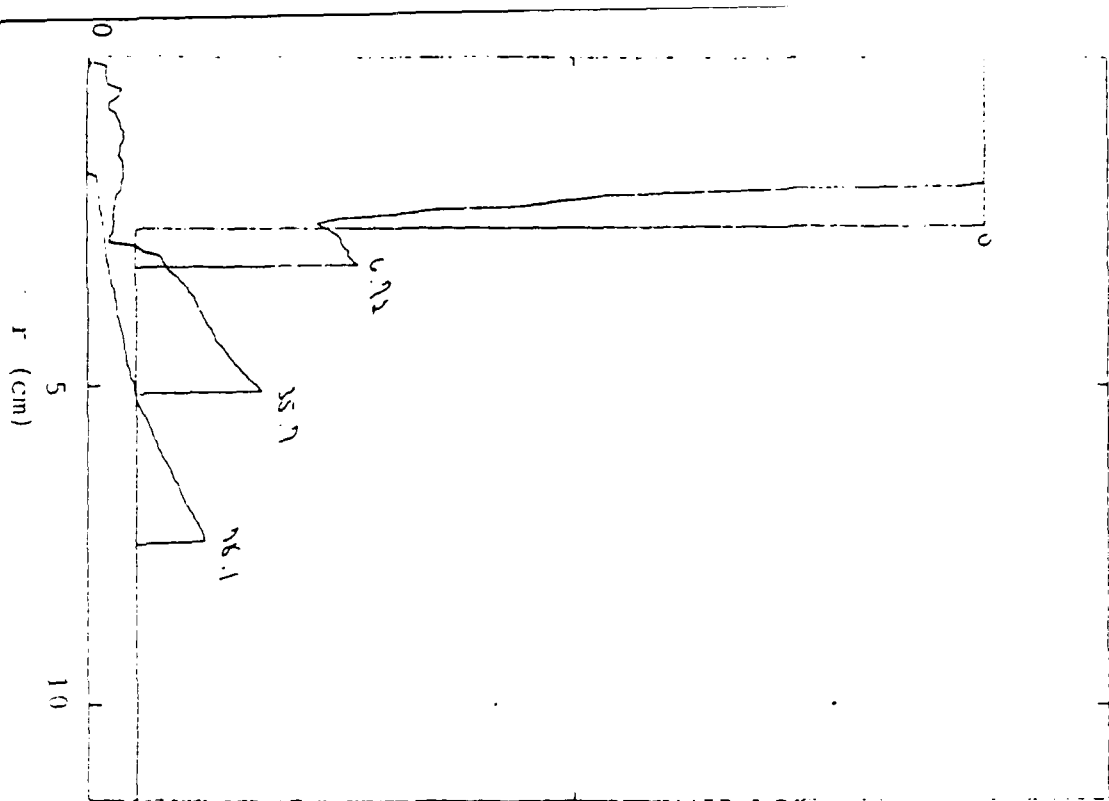


Figure 2. Comparison of the pressure profiles (normalized units) at several times for the helium bubble calculation of (a) Saito and Glass (from Prog. Aerospace Sci. 21 201-247 (1984)) and (b) the random choice code for this project. Time labels in (b) are in μ secs and correspond to the numbered curves in (a). The $t = 0$ profile is not shown in (a).



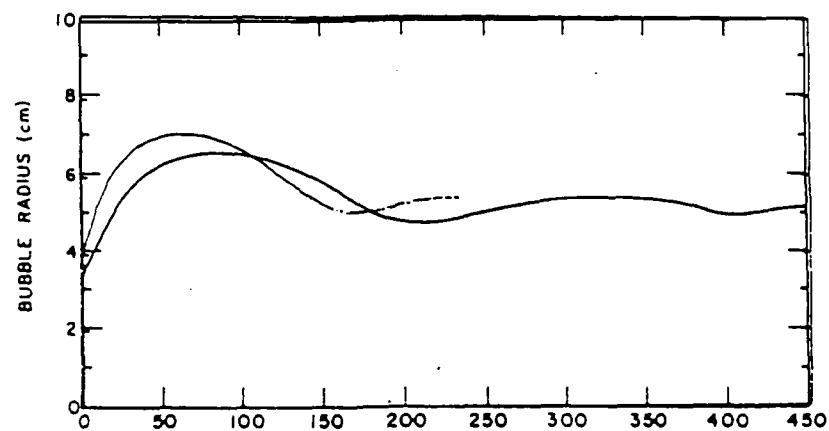


Figure 3. Superposition of plots of bubble radius (cm) versus time (μsec) for 0.55 pounds of tetryl detonated at 4.66 kbars ($\approx 156,000$ feet depth) as calculated by the SIN code up to 450 μsec and by the random choice code up to ≈ 250 μsec . The bubble in the tracked random choice calculation has a greater maximum and a shorter period. See the text for a discussion of the source of the differences.

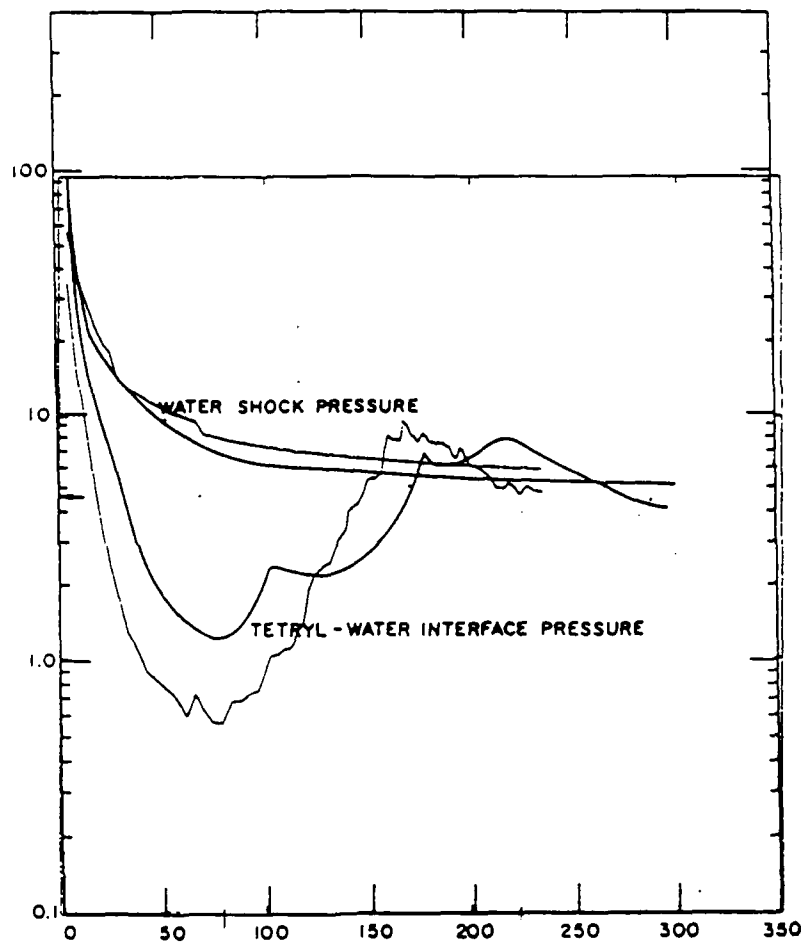


Figure 4. Superposition of plots of pressure versus time at the primary shock and at the gas-water interface for 0.55 pounds of tetryl detonated at 4.66 kbars ($\approx 156,000$ feet depth) as computed by the tracked random choice code (lighter curves) and by the SIN code. The random choice calculation underestimates the bubble pressure at the interface when the bubble is at its maximum extent. The pressure profiles at the primary shock agree more closely. See the text for a discussion of the source of the differences.

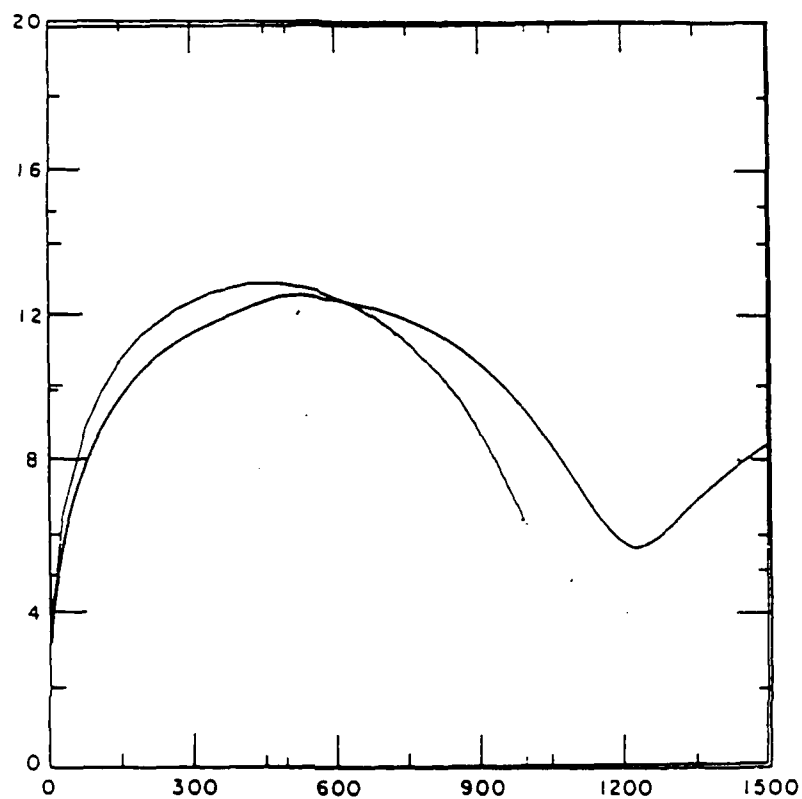


Figure 5. Superposition of plots of bubble radius (cm) versus time (μsec) for 0.55 pounds of tetryl detonated at 462 bars ($\approx 15,000$ feet depth) as calculated by the SIN code up to 1500 μsec and by the tracked random choice code up to ≈ 1000 μsec . The bubble in the tracked random choice calculation has a greater maximum and a shorter period. See the text for a discussion of the source of the differences.

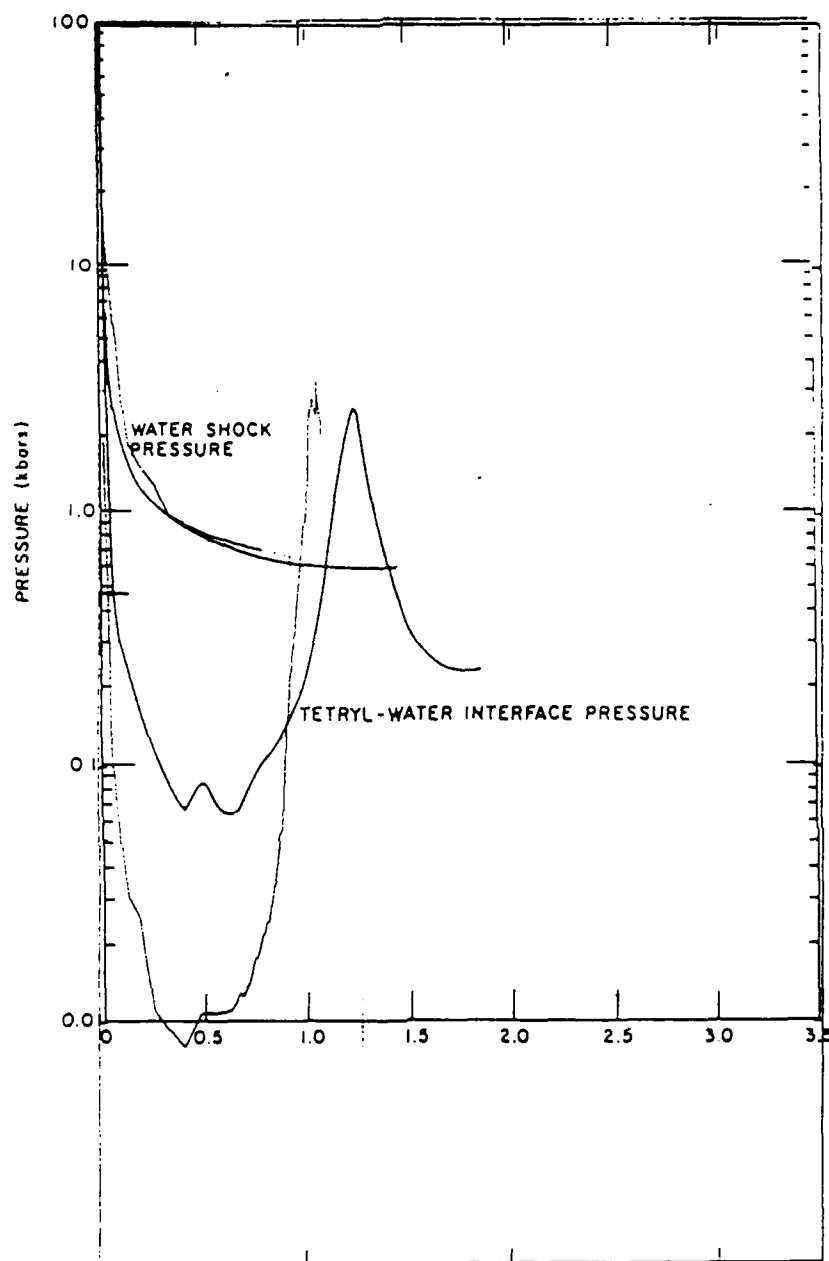


Figure 6. Superposition of plots of pressure (kbars) versus time (msec) at the primary shock and at the gas-water interface for 0.55 pounds of tetryl detonated at 462 bars ($\approx 15,000$ feet depth) as computed by the tracked random choice code (lighter curves) and by the SIN code. The tracked random choice calculation underestimates the bubble pressure at the interface by nearly an order of magnitude when the bubble is at its maximum extent. See the text for a discussion of the source of the differences.

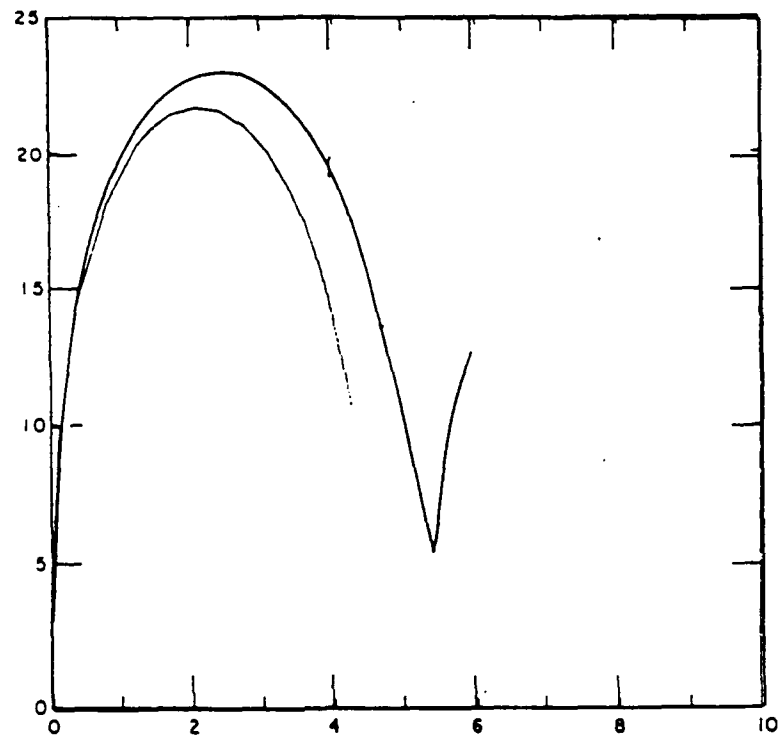


Figure 7. Superposition of plots of bubble radius (cm) versus time (msec) for 0.55 pounds of tetryl detonated at 74.6 bars ($\approx 2,500$ feet depth) as calculated by the SIN code up to 6 msec and by the random choice code up to ≈ 4.5 msec. The bubble in the tracked random choice calculation has a smaller maximum and a shorter period, unlike the calculations at the previous two depths. This results from the primary shock wave leaving the computational domain before the bubble reaches maximum radius, consistent with earlier results that have demonstrated the effect of using a domain which is too short.

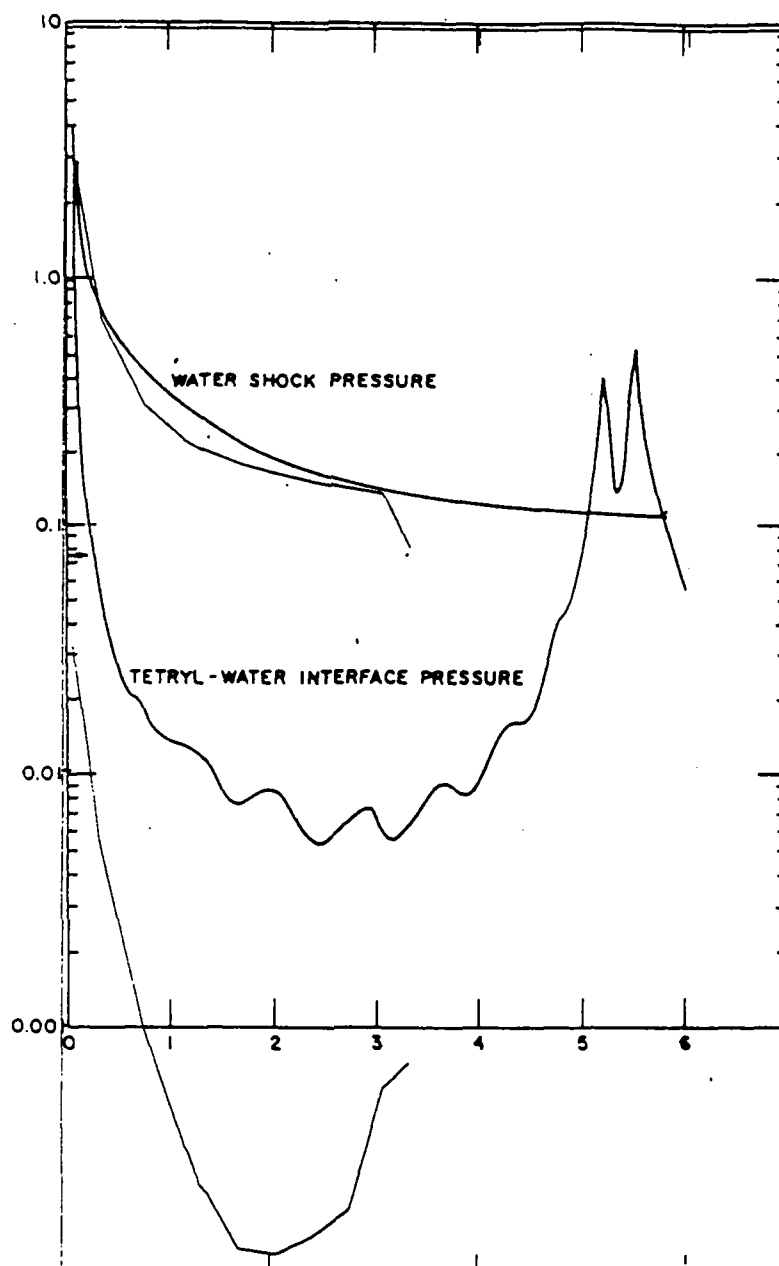


Figure 8. Superposition of plots of pressure (kbars) versus time (msec) at the primary shock and at the gas-water interface for 0.55 pounds of tetryl detonated at 74.6 bars ($\approx$ 2,500 feet depth) as computed by the tracked random choice code (lighter curves) and by the SIN code. The random choice calculation underestimates the bubble pressure at the interface by more than an order of magnitude when the bubble is at its maximum extent. The pressure profiles at the primary shock agree fairly well until the shock leaves the far boundary in the random choice calculation. See the text for a discussion of the source of the differences.