Advanced Fluid Modeling Capability for Underwater Shock Analysis of Naval Ships

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In accord with our Phase I Work Plan, this report presents the results of a series of underwater explosion (UNDEX) simulations done with two different computer programs. Our purpose here is to provide evidence of the complementary capabilities of the two codes while assessing their relative strengths and weaknesses. Our ultimate goal (at the end of Phase II) is to develop a computer program that accurately simulates critical UNDEX effects. Our strategy for doing this is to merge the best features of the two codes, thereby producing a single code with orders-of-magnitude improvement in computational efficiencies. Though more work will be needed to clarify unresolved issues, our Phase I results confirm the soundness of our strategy.

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ADVANCED FLUID MODELING CAPABILITY FOR UNDERWATER SHOCK ANALYSIS OF NAVAL SHIPS

Phase I Final Report: Contract N00014-01-M-0238

1. Introduction

Weidlinger Associates Inc. (WAI) and Florida State University (FSU) are pleased to submit this Final Report for our Phase I Cooperative Research Project. Our ultimate goal (at the end of Phase II) is to develop an advanced fluid modeling and simulation computer program that accurately predicts the physical effects that a ship or submarine would experience due to a nearby underwater explosion (UNDEX). Our strategy is to merge the best features of two different codes, FUSE (WAI) and CLSVOF (FSU), thereby producing a single code with orders-of-magnitude improvement in computational efficiencies. In accord with our Phase I Work Plan, this document presents the results of a series of UNDEX computations done with the two codes. The problems, which were selected from reference [1], were done to provide evidence of the complementary capabilities of the codes to simulate important physical effects while assessing their relative strengths and weaknesses. Though more work will be needed to clarify unresolved issues, our results confirm that our strategy is sound.

2. Background on FUSE and CLSVOF

When based on physical conservation principles (mass, momentum and energy), UNDEX computations involve detailed treatment of the high-pressure shock waves produced by the detonation, the expansion and collapse of the gas bubble containing the detonation products, the reflection of shock waves from interfaces (e.g., between air and water), bulk cavitation, bubble jetting, and many other physical effects that imperil Navy structures and personnel. Accurate simulations that include one or more expansion-collapse cycles of the gas bubble are widely considered to be challenging in just two dimensions (2D) and impractical in 3D. Although FUSE and CLSVOF are based on conservation, they employ different mathematical formulations, approximations and algorithms, thereby making them effective in different physical regimes. FUSE uses Lagrangian coordinates and explicit time integration to simulate shock waves in compressible materials. Although the time integration is based on an efficient, mixed explicit-explicit technique (called "subcycling"), this approach still requires extremely small time steps to satisfy numerical stability, leading to very lengthy computations for simulations that extend over one or more expansion-collapse cycles of the gas bubble containing the detonation products. In contrast, CLSVOF neglects the effects of waves propagating in compressible materials by treating the water as incompressible and approximating the detonation products as a simple vapor bubble while using Eulerian coordinates, semi-implicit time integration, coupled level-set, volume-of-fluid (CLSVOF) methods, and dynamic adaptive mesh refinement (AMR) that provides accurate resolution of small-scale (refined mesh) phenomena. Consequently, our Phase I proposal was focused on the possibility that CLSVOF would be more efficient than FUSE during much of a bubble's expansion-collapse cycle. An important Phase I goal, which we have achieved, is to demonstrate the feasibility of switching between the two codes, by starting a 2D bubble expansion-collapse problem with FUSE and then using the FUSE results as initial data for CLSVOF at a later time, when the nearly incompressible behavior of the water dominates, which is when FUSE is becoming relatively inefficient. Based on preliminary timing estimates, we can now say that the CLSVOF scheme is more efficient than FUSE over extremely large volumes of space (water) for long periods of time (more than 90% of a bubble's expansion-collapse cycle). The next few sections present the results of our Phase I work while focusing on the capabilities that will (when the codes are merged) enable accurate yet efficient modeling of critical UNDEX effects.

3. Background on UNDEX Test Problems

Reference [1] presents nineteen UNDEX problems, specifying various details (equations of state, computational meshes, etc.) for each one. Because 2D problems that include one or more expansion-collapse cycles of the gas bubble are computationally challenging, we selected a series of problems that would enable us to assess the capabilities of FUSE and CLSVOF to deal with problems of this kind. The author of [1] provided us with benchmark (i.e., converged) solutions in the form of digitized data for most problems, and provided graphical results for a problem that has no benchmark. The equations of state (EOS) specified in [1] are of the form $p = p(\rho, e)$ where p is pressure, ρ is mass density and e is internal energy. The EOS specified for the detonation products is a standard Jones-Wilkins-Lee (JWL) model

$$p = A\left(1 - \frac{\omega\rho}{R_1\rho_0}\right)\exp(-\frac{R_1\rho_0}{\rho}) + B\left(1 - \frac{\omega\rho}{R_2\rho_0}\right)\exp(-\frac{R_2\rho_0}{\rho}) + \omega\rho e\,.$$

Different problems have different JWL constants. The EOS specified for water is a modified Tait model,

$$p = \begin{cases} B\left[\left(\dfrac{\rho}{\rho_0}\right)^{\gamma} - 1\right] + A & \text{if } \rho > \rho_c, \\ p_c & \text{otherwise,} \end{cases}$$

where p_c is called the cavitation pressure, $\gamma = 7.15$, $\rho_0 = 1.\,\text{g/cm}^3$, $A = 1.\text{E}+6\,\text{d/cm}^2$, $B = 3.31\text{E}+9\,\text{d/cm}^2$, $\rho_c = 1.0 - 4.225\text{E}-5\,\text{g/cm}^3$, $p_c = 220.2726\,\text{d/cm}^2$.

4. Spherical Bubble Collapse in 1D

Spherical Bubble Collapse, Problem I.F in [1], is cast in 1D spherical coordinates with $R\,(\text{cm})$ as the radial coordinate and $u\,(\text{cm/sec})$ as the radial velocity. This problem, which neglects gravity and corresponds to about 28 kg of explosive material detonated in open water at a depth of 91.6 meters, starts at time $t = 0$ with a spherical bubble of high-pressure JWL material surrounded by water. The bubble radius is initially equal to 16 cm, and the initial material states are:

JWL: $\rho = 1.63$, $e = 4.2814E+10$, $p = 7.8039E+10$, $u = 0$

Water: $\rho = 1.00037984$, $e = \mathrm{N/A}$, $p = 1.\mathrm{E}+7$, $u = 0$.
The problem simulation time is $0 < t < 150$ msec, which is somewhat longer than one expansion-collapse cycle of the bubble containing the JWL material, for which the specified constants are $A = 5.484\mathrm{E}+12\ \mathrm{d/cm}^2$, $B = 0.09375\mathrm{E}+12\ \mathrm{d/cm}^2$, $R_1 = 4.94$, $R_2 = 1.21$, $\omega = 0.28$, $\rho_0 = 1.63\ \mathrm{g/cm}^3$. For this problem, the author of [1] provided us with digitized benchmark data obtained from a converged mesh, interface-tracking solution that used 1,024 cells inside the bubble's interface and 565 points outside.

Although [1] specifies three non-uniform 1D computational meshes (8, 16 and 32 equal-sized cells inside the bubble radius, etc.), we present results from three FUSE computations done with initially uniform meshes that have the specified number of cells inside the bubble. The cells do not remain equal in size however because FUSE uses a Lagrangian mesh. Figure 1 shows the bubble radius versus time from the three FUSE computations, and Figure 2 compares the finest-mesh FUSE solution to the benchmark data. From the benchmark data, the first bubble collapse is at 132.4 msec with the minimum bubble radius equal to 29.3 cm, whereas the first bubble collapse for this FUSE solution occurs at 135.9 msec with the minimum radius equal to 27.8 cm. Relative to the benchmark, the FUSE errors for this mesh are +2.7% for the collapse time and –5% for the minimum radius. The differences between the benchmark and FUSE results are chiefly due to the fact that the benchmark mesh had 1,024 cells inside the bubble whereas the finest FUSE mesh had only 32 cells. We show this in Figures 3 and 4, which compare the benchmark pressure and velocity distributions to the finest-mesh FUSE solution at t=4.96 msec, when the bubble radius is about R = 100 cm, about six times its original radius of 16 cm. Inside the bubble, the benchmark distributions exhibit higher and sharper details than the FUSE distributions, consistent with the large number of cells inside the benchmark bubble. However, the reverse is true in the water, particularly at the shock front (near $R = 900\,\mathrm{cm}$) where the FUSE results are higher and sharper than the benchmark. This occurs because the benchmark solution was obtained with only 565 points outside the bubble whereas the FUSE mesh was initially uniform, leading to a finer FUSE mesh in the water. As Figures 5 and 6 show, the same remarks apply to the distributions at t=13.4 msec, when the bubble radius is about R = 140 cm.

We spent considerable time comparing FUSE 1D results to the benchmark data provided to us, by analyzing different quantities, by using various meshes, and by solving other problems for which we have benchmark data (e.g., problems I.B and I.E, which are early-time 1D problems that are closely related to Problem I.F), but found it was impractical to continue along these lines within the resources of this contract. In view of the coarseness of the three meshes prescribed in [1], we have concluded that, although the differences are of academic interest, our FUSE 1D solutions are acceptable for engineering applications of explosion mechanics (even with just 8 cells inside the bubble). Since 2D problems are more challenging and of more significance than 1D problems, we consider only 2D problems in the rest of this proposal.

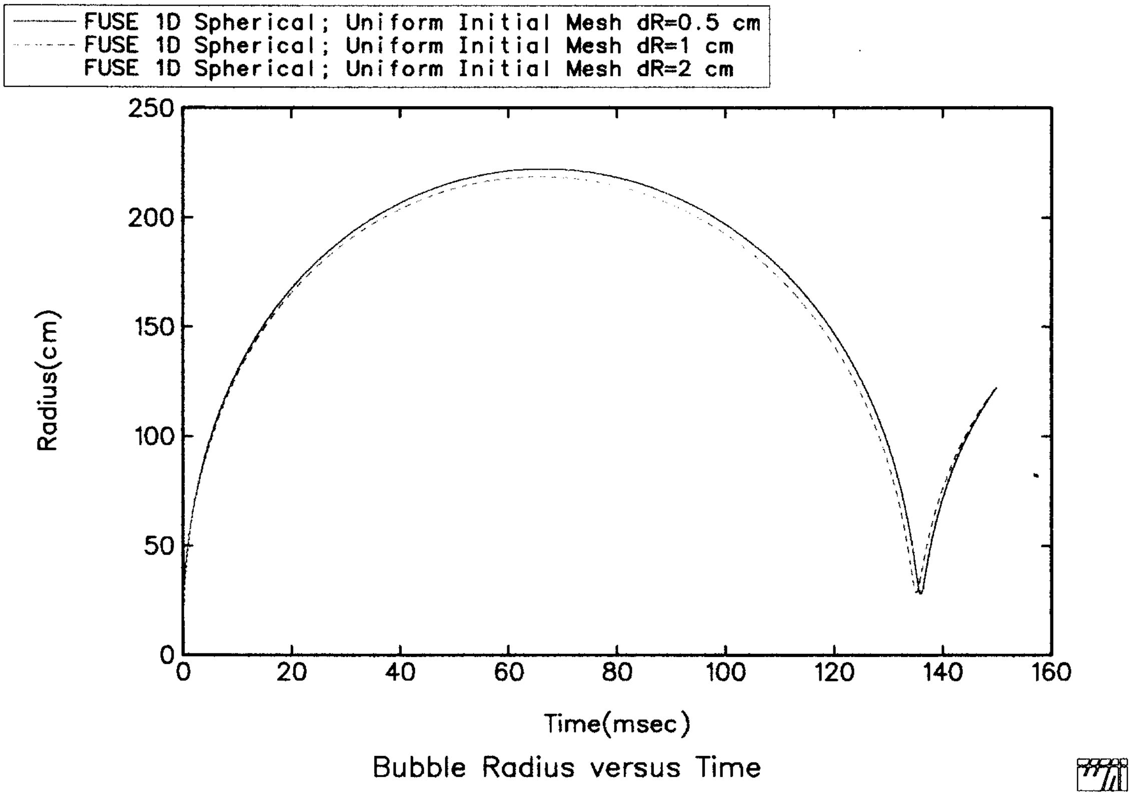


Figure 1. Three FUSE solutions (32, 16 and 8 cells inside the bubble), Problem I.F

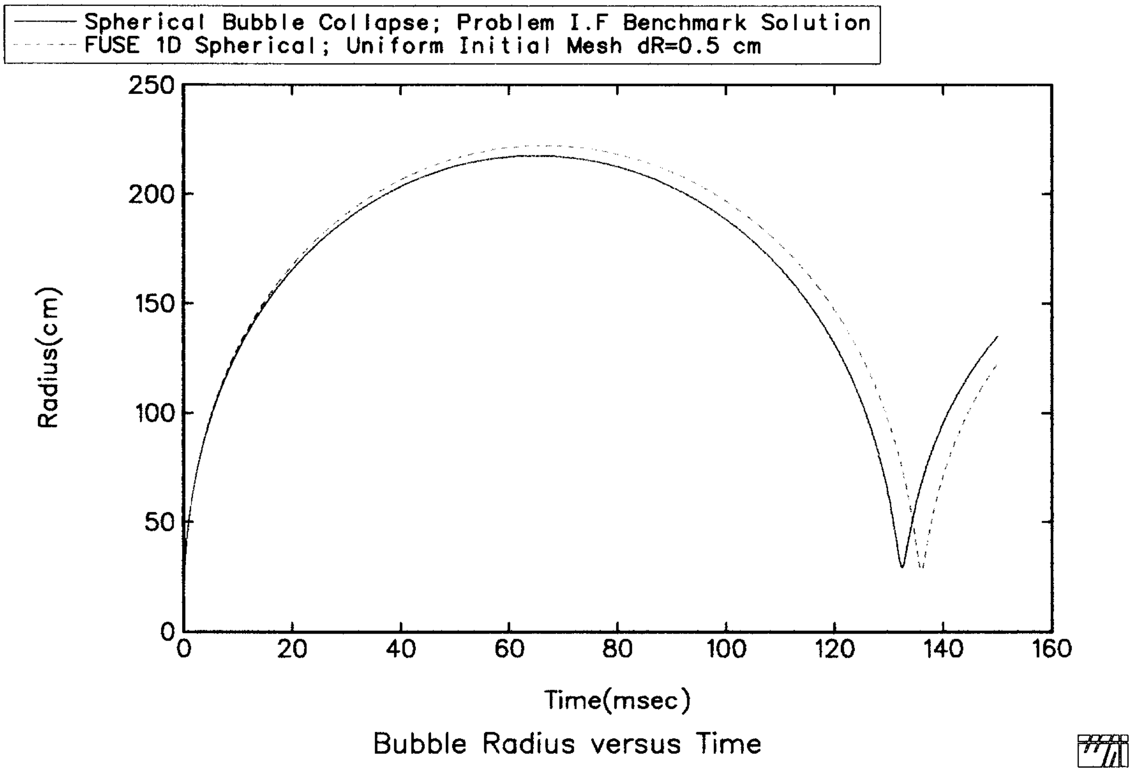


Figure 2. FUSE (32 cells inside the bubble) compared to Benchmark, Problem I.F

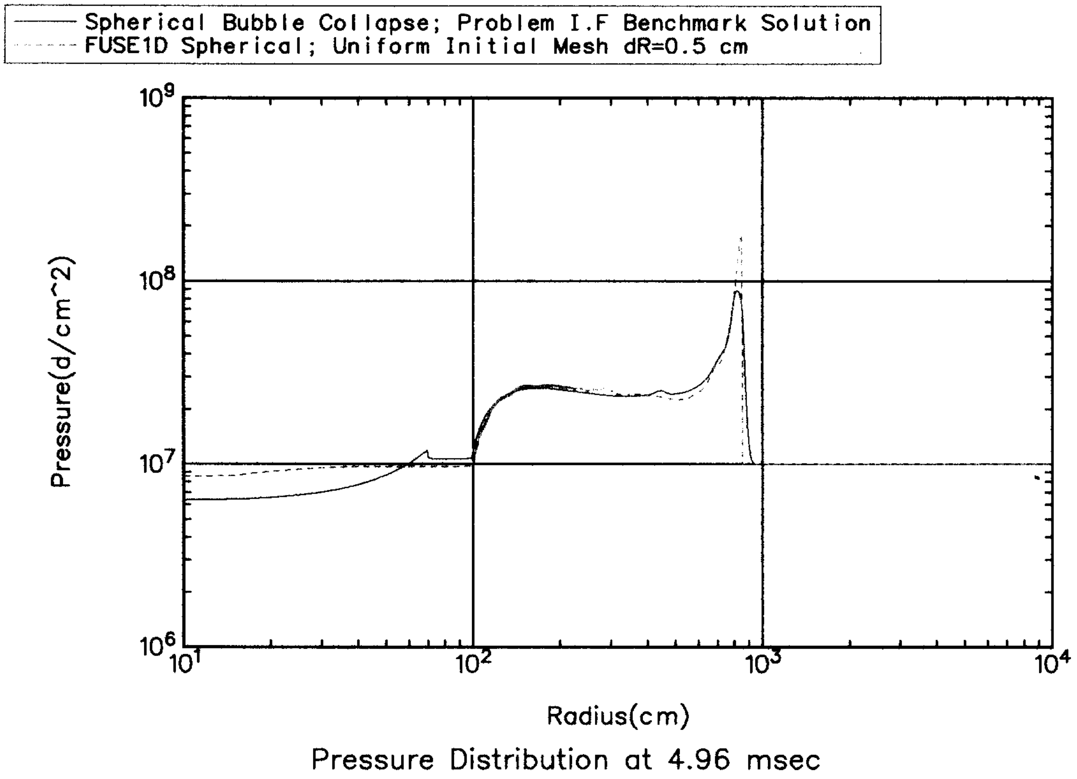


Figure 3. FUSE compared to Benchmark, Problem I.F

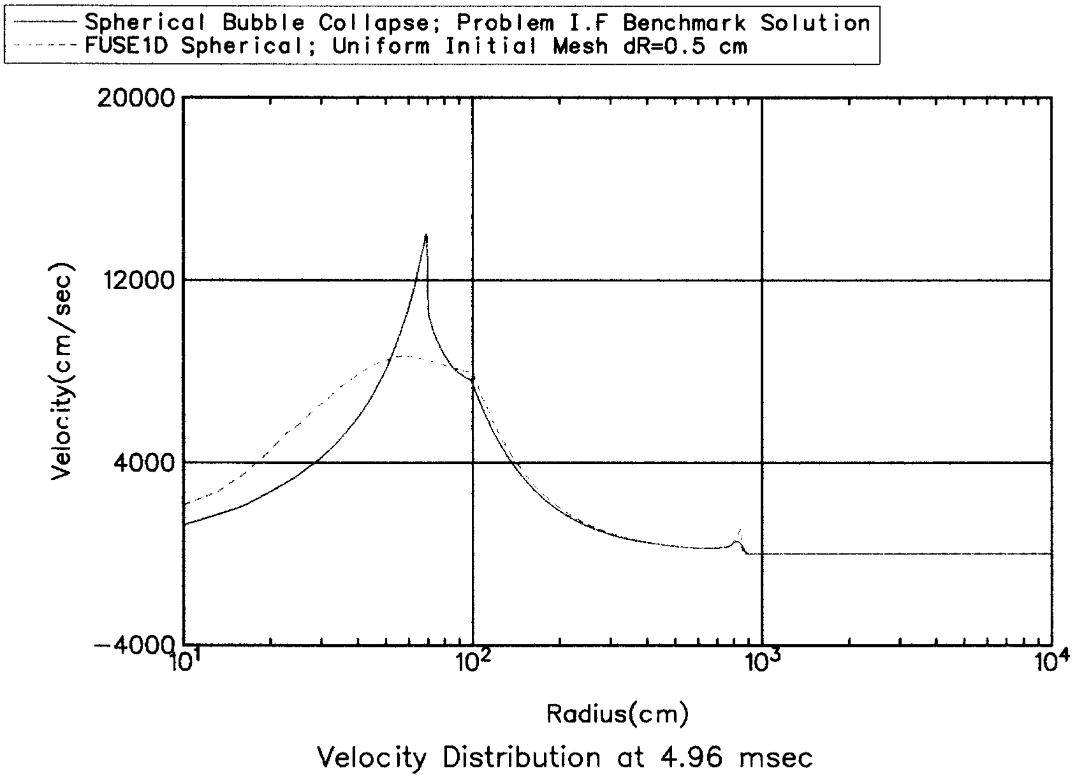
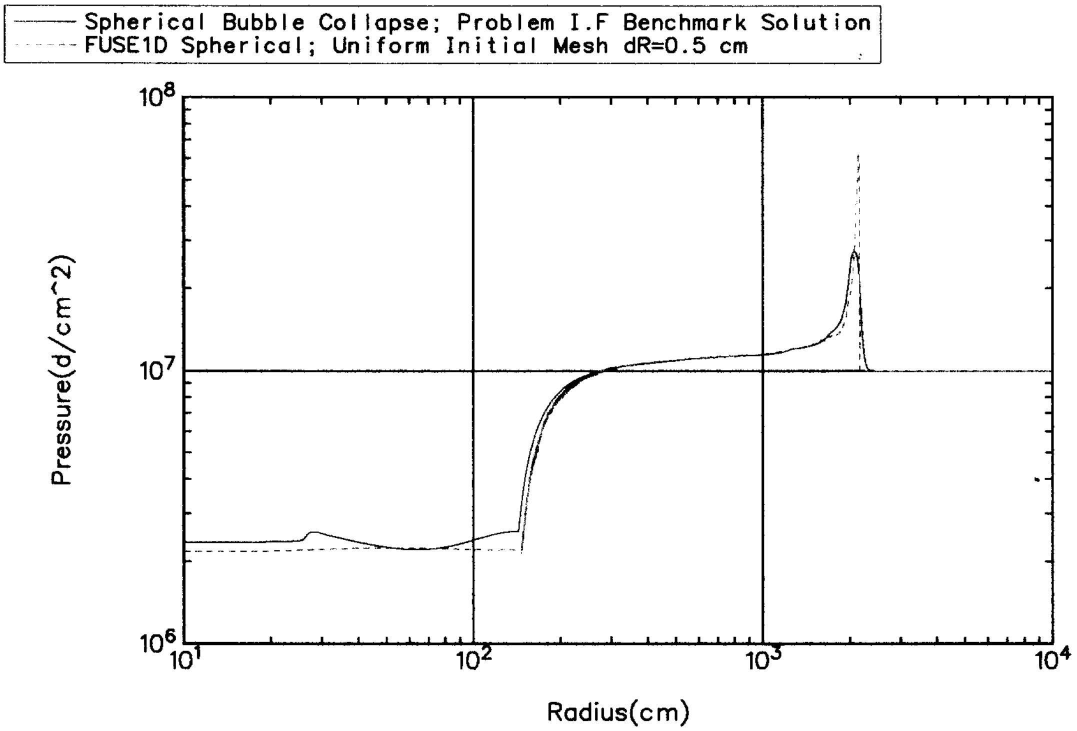
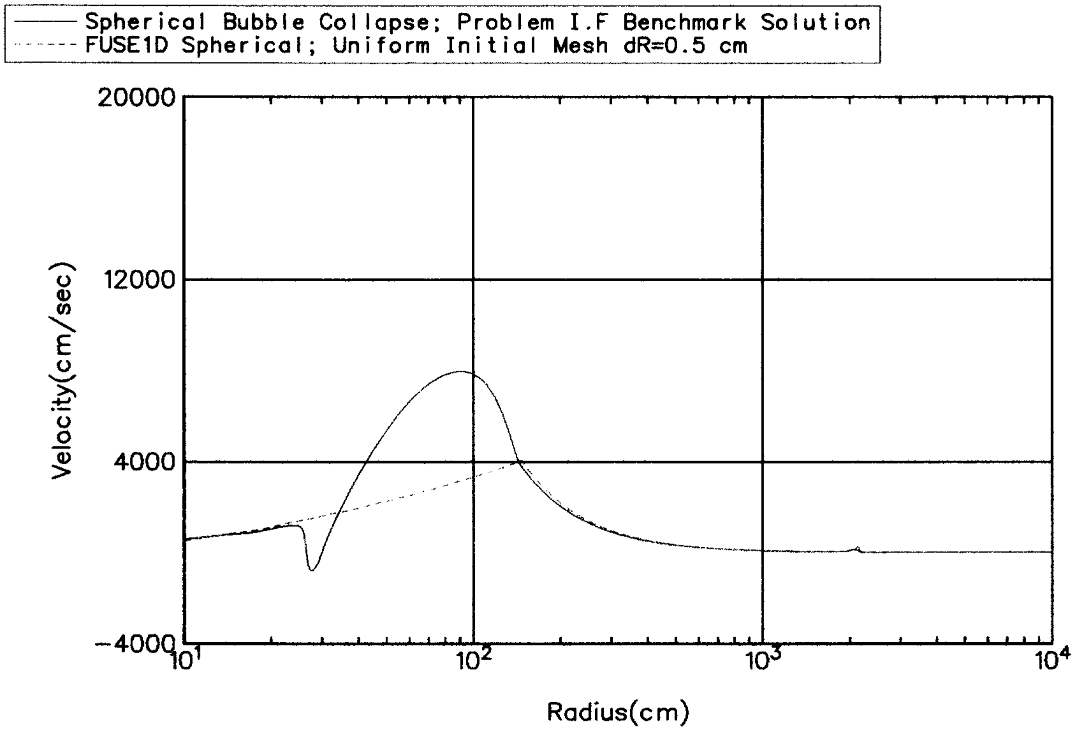


Figure 4. FUSE compared to Benchmark, Problem I.F



Pressure Distribution at 13.4 msec

Figure 5. FUSE compared to Benchmark, Problem I.F



Velocity Distribution at 13.4 msec

Figure 6. FUSE compared to Benchmark, Problem I.F

5. Spherical Bubble Collapse in 2D

Spherical Bubble Collapse in 2D, Problem II.C in [1], is physically identical to the 1D problem (I.F) discussed in the previous section, but is cast in cylindrical coordinates r, z. We start our computations with FUSE 1D and, at various times soon after detonation, switch to CLSVOF 2D by using the FUSE results as initial data for CLSVOF. As anticipated, we find that even if the switch is done as early as 2 or 3 msec after detonation, the CLSVOF results are accurate for long periods of time over large regions of space. A major achievement of our research thus far is to confirm (tentatively) that CLSVOF is much more efficient than FUSE for most (>90%) of the expansion-collapse cycle of the gas bubble. Our work also highlights the fact that CLSVOF neglects important wave propagation effects, albeit only for short periods of time in relatively small regions of space. If awarded a Phase I Option, an important part our work would be to clarify the issues associated with these statements.

Figure 7, which shows the bubble radius versus time, compares the benchmark data with results from CLSVOF started at $t = 13.4$ msec, which is 10% of the first bubble period. The two CLSVOF curves show bubble radius as it moves along the diagonal line (as specified in [1]) in the 2D cylindrical mesh. Because CLSVOF uses dynamic adaptive mesh refinement (AMR), Figure 7 shows results from two different computations labeled AMR=4 Levels and AMR=5 Levels. AMR=4 means that the maximum number of levels of local mesh refinement was limited to 4 during the computation. Since each level corresponds to locally refining the mesh by another factor of two (as required based on error criteria), AMR=5 means that the computation allowed another factor of two in the local mesh refinement (if needed). Figure 8 compares pressure versus radius at $t = 66.4$ msec, which is the time when the benchmark bubble is at its maximum radius (about 14 times the initial radius). Figure 8 shows results from the benchmark, from CLSVOF 2D along the diagonal using AMR=5, and from FUSE 1D using the finest mesh. There is no CLSVOF data beyond R=7,000 cm because the CLSVOF boundaries far from the center of the explosion were restricted by that distance with the far boundary pressure being set to the ambient water pressure $p = 1.\mathrm{E}+7$. However, even if there were CLSVOF results beyond R=7,000 cm, they would not agree beyond that distance with the other two solutions, especially in the vicinity of the shock front near R=10,000 cm because CLSVOF, being an incompressible fluids code, does not include wave propagation effects. As to the relative efficiency, preliminary timing estimates indicate that CLSVOF is an order of magnitude faster than FUSE 2D for this problem. Additional work will be needed to clarify and resolve important issues.

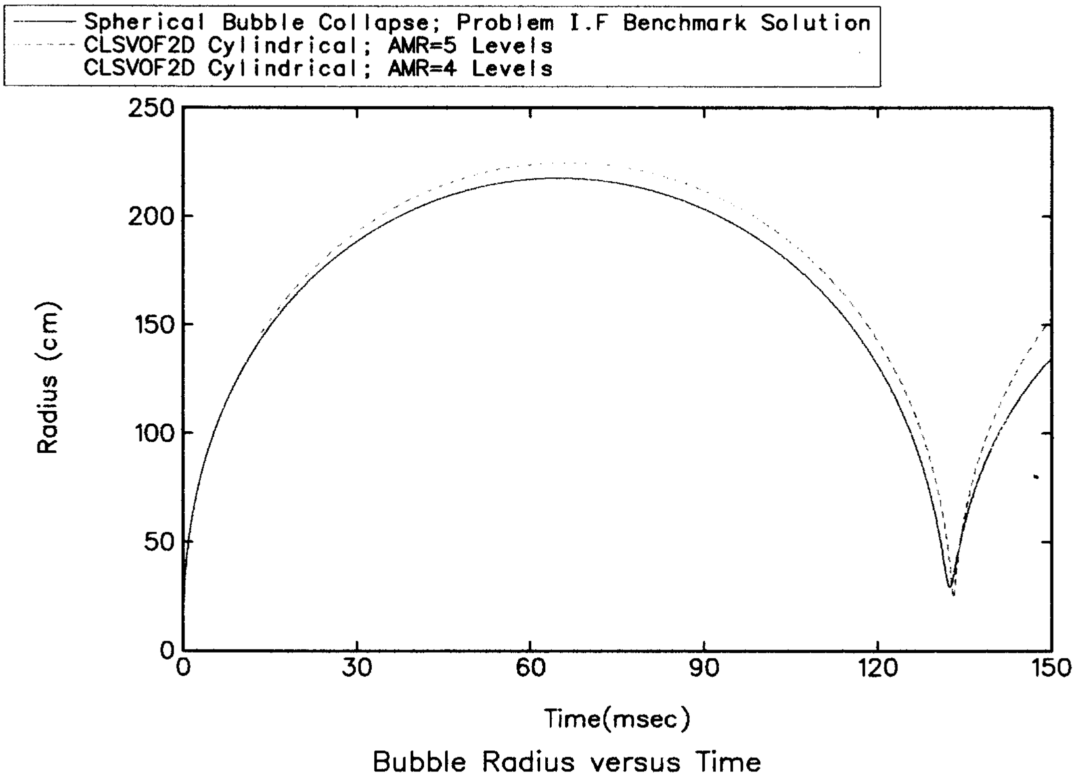


Figure 7. CLSVOF 2D started at 13.4 msec, radius along diagonal; Problem II.C

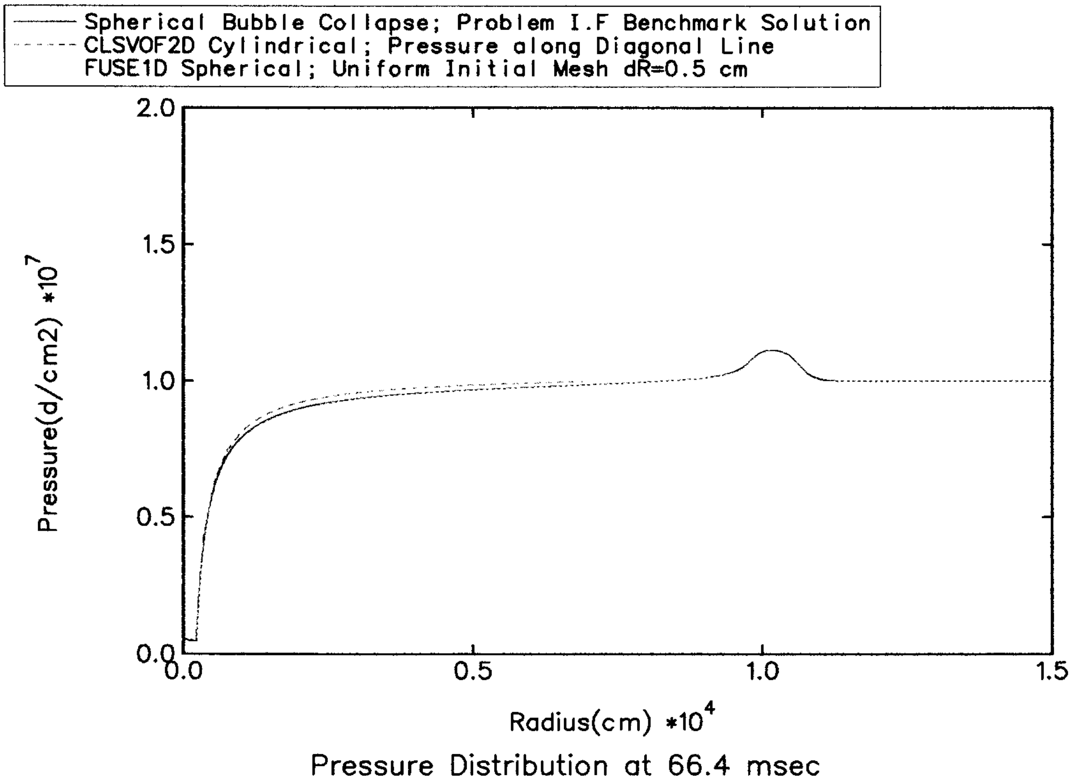
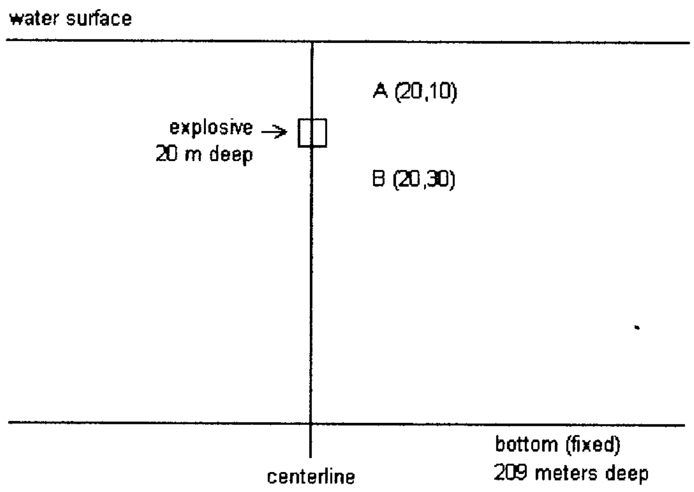


Figure 8. CLSVOF 2D started at 13.4 msec, pressure along diagonal, Problem II.C

6. Free Field Cavitation



Free Field Cavitation, Problem II.H in [1], is also cast in 2D cylindrical coordinates r, z. The problem sketch at right) corresponds to 250 kg of explosive material, detonated at depth of 20 meters at the time $t = 0$ in open water 209 meters deep. The initial shape of the explosive is a cylinder, 58 cm in diameter and 58 cm high. Gravity is included and the simulation time is $0 < t < 130$ msec. The explosive is modeled as JWL material, the specified constants being $A = 3.712\text{E} + 12\ \text{d/cm}^2$, $B = 0.03231\text{E} + 12\ \text{d/cm}^2$, $R_1 = 4.94$, $R_2 = 1.21$, $\omega = 0.28$, $\rho_0 = 1.63\ \text{g/cm}^3$. Initial material states are

JWL: $\rho = 1.63$, $e = 4.294479E + 10$, $p = 8.38369E + 10$, $u = 0$

Water (depth of 20 m): $\rho = 1.00008343$, $e = \text{N/A}$, $p = 2.975\text{E} + 6$, $u = 0$.

The physics of this problem is quite different from Spherical Bubble Collapse since the mass of explosive is greater (ratio 8.9) and the depth of the burst is shallower (ratio 0.22). The dominant physical effect during the simulation time is high-pressure shock waves reflecting from the water's free surface, which creates large regions in the water where the absolute pressure is practically zero, a phenomenon called bulk cavitation. There is no benchmark solution for Free Field Cavitation but the author of [1] provided us with graphical output from a computation that used a non-uniform mesh consisting of 210 radial cells by 297 vertical cells. We compare those results to FUSE results from a computation that used a non-uniform mesh of 607 by 612 cells. Although the FUSE mesh is more refined, we do not claim our results are more accurate. Rather, our purpose here is to prepare a foundation for proposing a Phase I Option, part of which will involve assessing the pros and cons of using CLSVOF when solving problems involving important UNDEX phenomena such as bulk cavitation.

Figure 9 shows a colorized contour plot of the FUSE pressure field at t=25 msec, which compares favorably with Figure 10, the corresponding plot provided to us by the author of [1]. In Figure 9, where black indicates cavitated cells (i.e., the cells where the water pressure equals $p_c = 220.2726\ \text{d/cm}^2$), the large black region is quite similar in size and shape to the large cavitated region outlined by a black curve in Figure 10. Among other provided graphs was a curve of cavitated volume versus time. Although our cavitated volume agrees reasonably at t=25 msec and before, we found this quantity was unreliable due to its sensitivity to numerical details such as the choice of mesh and the amount of artificial viscosity. This sensitivity indicates that we have not achieved a mesh-converged solution for this problem. Hence, we do not show cavitated volume versus time. Using other graphs provided to us, we digitized the pressure versus time curves corresponding to points A and B (radius and depth in meters are shown in parentheses in the sketch). Although absolute pressure was used in all FUSE computations (as specified in [1]), we compare results in terms of the effective pressure (i.e., absolute pressure minus the static pressure at the depth of each point, also called "live" pressure), which is a sensible measure of the load that a nearby structure would experience as a result of the explosion. Figures 11-14 compare the effective pressure and the effective impulse (the integral of the effective pressure with respect to time) at points A and B[1].

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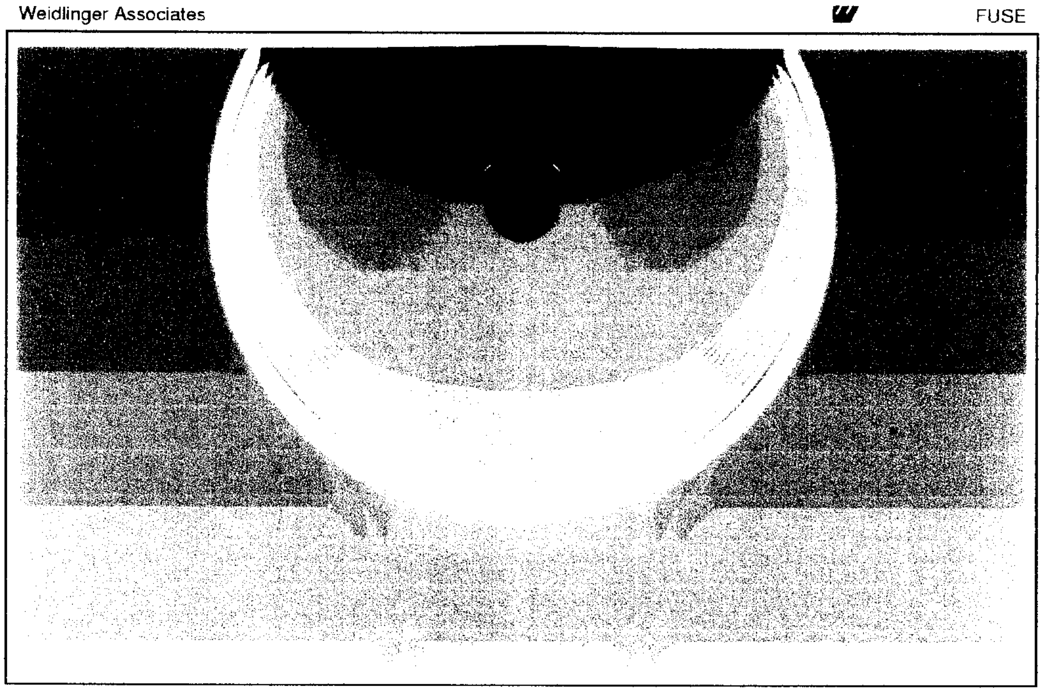
[1] While writing this report but too late to test the idea, we suspect some of the differences in Figure 11-14 are due to the fact that the points A and B are fixed in space (Eulerian mesh) in the case of the data provided by the author of [1] whereas the points A and B are moving in FUSE (Lagrangian mesh). This speculation is consistent with the overall agreement in these figures since the displacements are not large at or near these points during the relatively short simulation time (130 msec).



FUSE: Free Field Cavitation at t=25 msec (compare to next figure)

Figure 9. FUSE 2D Free Field Cavitation, Problem II.H, pressure contours at 25 msec, black shows cavitated cells, compare to Figure 10.

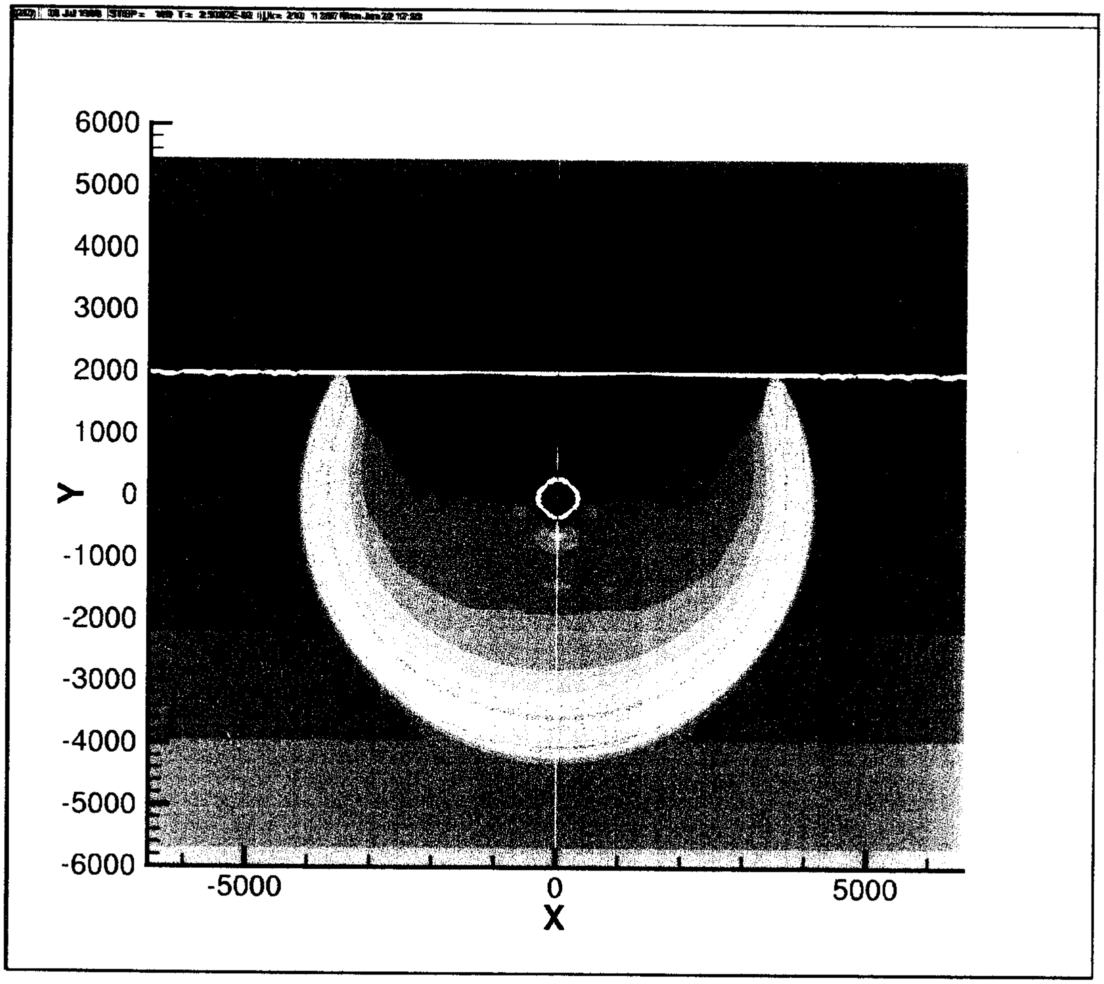


Figure 10. Provided by the author of reference [1], Free Field Cavitation, Problem II.H, pressure contours at 25 msec, cavitated regions are outlined by black curves; compare to Figure 9

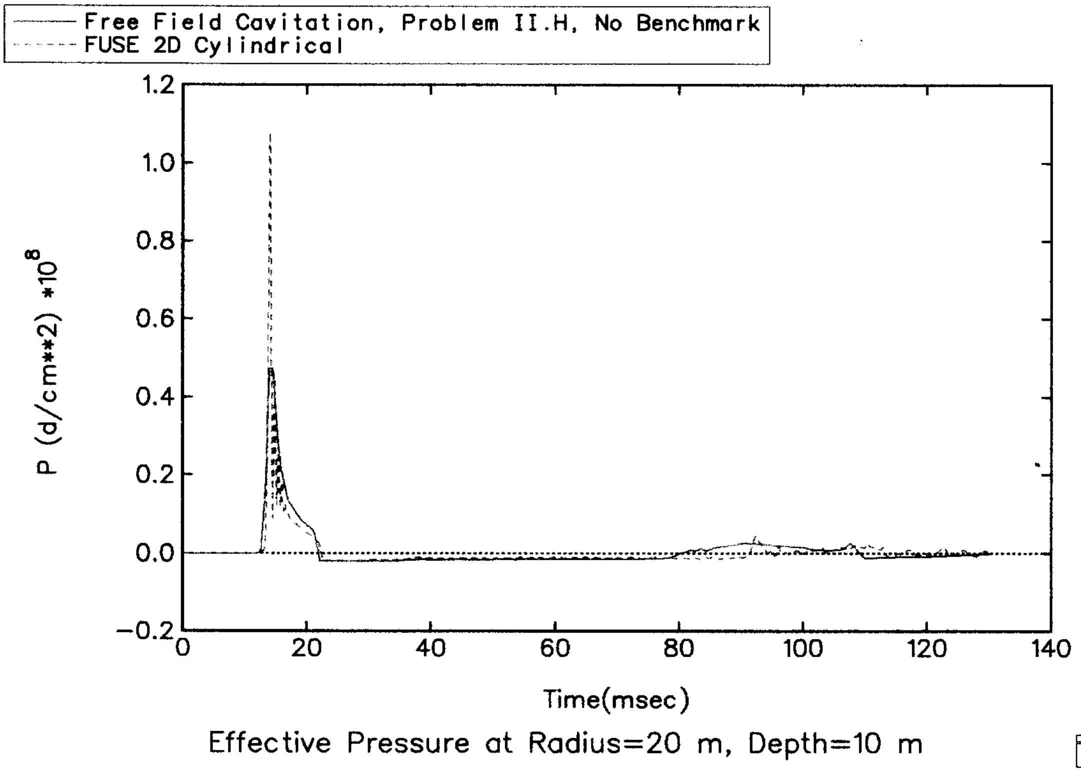


Figure 11. FUSE 2D compared to Digitized Data (Point A), Problem II.H

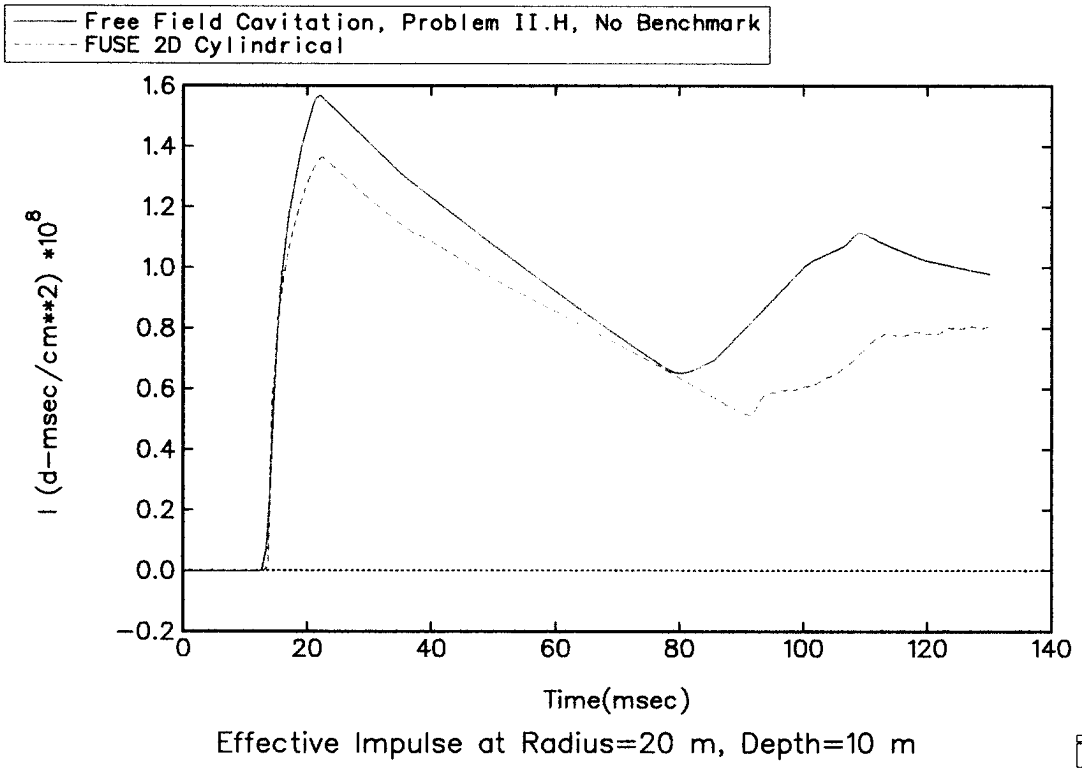
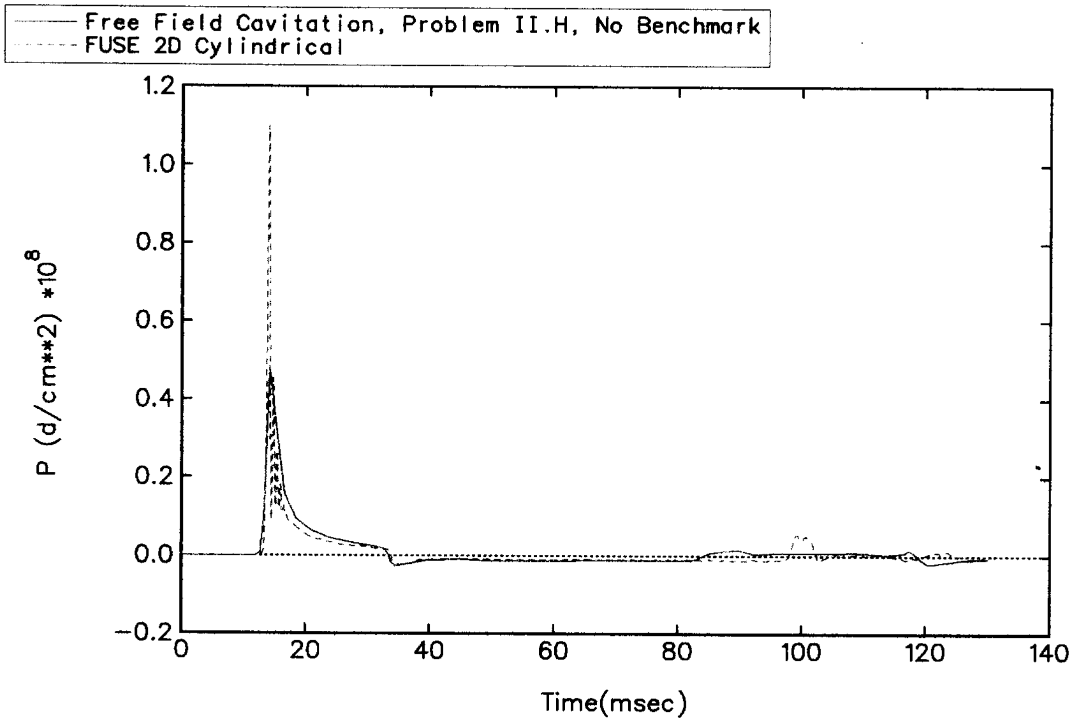
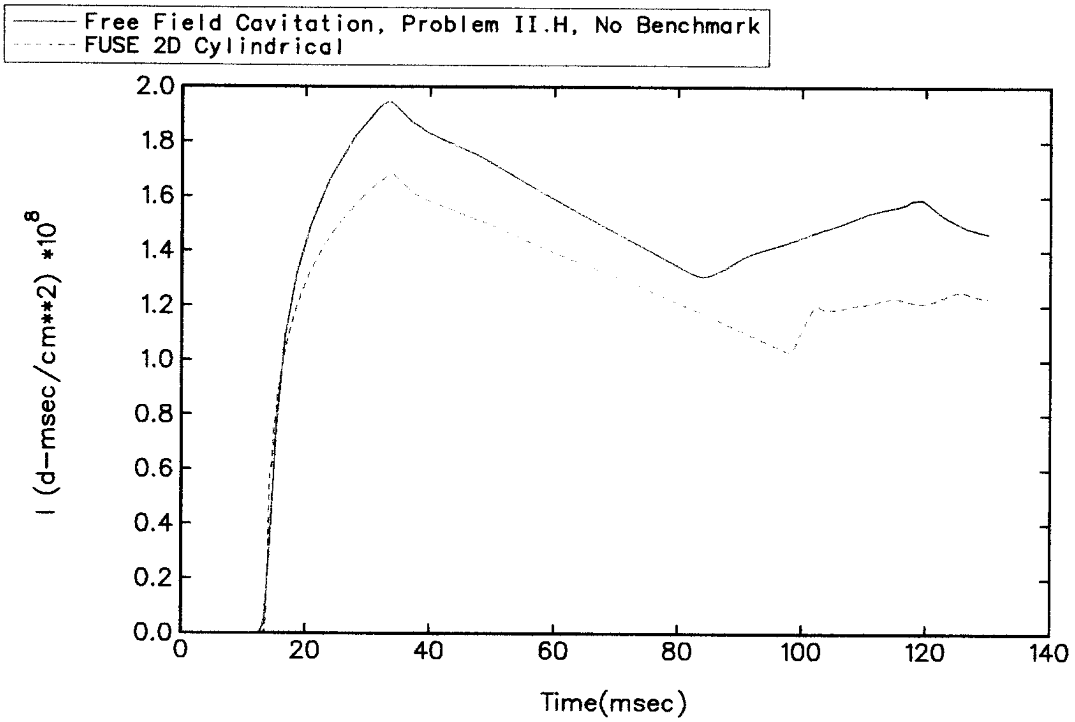


Figure 12. FUSE 2D compared to Digitized Data (Point A), Problem II.H



Effective Pressure at Radius=20 m, Depth=30 m

Figure 13. FUSE compared to Digitized Data (Point B), Problem II.H



Effective Impulse at Radius=20 m, Depth=30 m

Figure 14. FUSE compared to Digitized Data (Point B), Problem II.H

7. Outline of Phase II Plans for Merging CLSVOF and FUSE

As was mentioned previously, FUSE and CLSVOF employ different approximations and algorithms, leading to complementary capabilities that are effective in different physical regimes. So far, our Phase I work on Spherical Bubble Collapse in 2D showed that CLSVOF is more efficient than FUSE in large regions of space where water's incompressibility dominates for long periods of time. As detailed in our Phase I Proposal, we plan to exploit this by merging CLSVOF and FUSE, thereby creating an accurate yet efficient computer program for simulating UNDEX problems. Specifically, we plan to devise criteria that determine where and when materials (cells in the computational mesh) will be treated as compressible or incompressible. This must be done carefully, in a way that will not introduce discontinuities. Once these criteria have been developed, the algorithms for doing this will be based on level-set methods and ghost-fluid techniques, which are well suited to deal with discontinuous functional behavior in a physically correct way. We also plan to retain dynamic adaptive mesh refinement (AMR) to enhance accuracy and efficiency. In addition, we plan to devise a mixed implicit-explicit time integration method that will combine the semi-implicit scheme in CLSVOF and the explicit-explicit scheme in FUSE. We plan to merge capabilities by adopting CLSVOF as our base code since its best features (Eulerian mesh, dynamic adaptive mesh refinement, level-set methods, volume-of fluid interface scheme, semi-implicit time integration) are well tuned for incompressible flow, which dominates the physics throughout much of time and space. We will adapt the best features of FUSE (detonation physics, wave propagation, mixed explicit-explicit time integration) to CLSVOF. This is achievable because the WAI/FSU team has the essential background, experience and skills required to produce the envisioned innovative software.

8. Summary of Work Plan for Phase I Option

Considering our Phase I results, we would propose a Phase I Option to extend our current work, thereby allowing us to focus on CLSVOF, which we plan to use as our base code during Phase II code development. Our primary goal during Phase I Option will be to obtain better estimates of the relative accuracies and efficiencies of FUSE and CLSVOF while solving more realistic 2D problems involving wave propagation effects. Specifically, we would propose to use CLSVOF to do Free Field Cavitation (II.H) to assess the role of the near-incompressible nature of water. Since our FUSE 2D results compare reasonably with known results (previous section), this would enable us to study the relative computational efficiency of CLSVOF when doing a problem that involves waves reflecting from the water's free surface, producing bulk cavitation. As with Spherical Bubble Collapse in 2D, we would start Free Field Cavitation with FUSE and then switch to CLSVOF at different times soon after detonation (significantly less than 25 msec) while studying the relative accuracy and efficiency of the codes. In addition (or alternatively), we would propose to compare results for a 2D problem involving waves reflecting from a rigid surface, which is a simplification of Bubble Jetting, Problem II.E.

In summary, our work under Phase I Option would include more realistic 2D computations involving various wave propagation phenomena while focusing on the pros and cons of using CLSVOF as our base code. This would allow us to identify the most effective CLSVOF algorithms and software, which would be retained when merging software in Phase II. We would also examine key software portions of FUSE, which is coded in Fortran, while considering how to transfer them to CLSVOF, which is a mixture of C++ at the higher levels and Fortran at the computationally intense, lower levels. This would enable us to establish programming conventions that would be used in our Phase II work, which would entail developing the final code.

9. References

[1] *Underwater Explosion Test Cases* by Andrew B. Wardlaw, Jr., Technical Report IHTR 2069 (DTIC number: ADB238684), Naval Surface Warfare Center, Indian Head, MD (1998).