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# DYNAMICS OF WATER CAVITY GENERATION

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## ABSTRACT

The hypervelocity impact (1.25 to 6 km/sec) of projectiles into water has been studied at the University of Arizona by Gault and Sonett. They observed quite different behavior of the water cavity as it expanded when the atmospheric pressure was reduced from one to a tenth atmosphere. Above about a third of an atmosphere, a jet of water formed above the expanding bubble and a jet or "root" emerged below the bottom of the bubble.

Similar results were observed by Kedrinskii at the Institute of Hydrodynamics in Novosibirsk, Russia when the water cavity was generated by exploding bridge wires with jets and roots forming for normal atmospheric pressure and not for reduced pressures.

Earlier at the Los Alamos National Laboratory B. G. Craig, reported observing the formation of jets and roots while the gas cavity was expanding by bubbles generated by small spherical explosives detonated near the water surface.

During the last decade a compressible Eulerian hydrodynamic code called SAGE has been under development by the Los Alamos National Laboratory and Science Applications International (SAIC) which has continuous adaptive mesh refinement (AMR) for following shocks and contact discontinuities with a very fine grid while using a coarse grid in smooth flow regions.

A version of the SAGE code that models explosives called NOBEL has been used to model the experimental geometries of Sonett and of Craig. The experimental observations were reproduced as the atmospheric pressure was varied. When the atmospheric pressure was increased the difference between the pressure outside the ejecta plume above the water cavity and the decreasing pressure inside the water plume and cavity as it expanded resulted in the ejecta plume converging and colliding at the axis forming a jet of water proceeding above and back into the bubble cavity along the axis. The jet proceeding back thru the bubble cavity penetrates the bottom of the cavity and forms the root observed experimentally. The complicated bubble collapse and resulting cavity descent into deeper water was numerically reproduced.

Now that a code is available that can describe the experimentally observed features of projectile interaction with the ocean, we have a tool that can be used to evaluate impact landslide, projectile or asteroid interactions with the ocean and the resulting generation of tsunami waves.

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## INTRODUCTION

The process of cavity generation by projectiles or explosives in the ocean surface and the resulting fluid flows has been an important unsolved problem for over 50 years. The prediction of water waves generated by large-yield explosions and asteroid impacts has been based on extrapolation of empirical correlations of small-yield experimental data or numerical modeling assuming shallow water waves. The "upper critical depth" is an experimentally observed wave height maximum that occurs when an explosive charge is approximately two-thirds submerged. The observed height at the upper critical depth is twice that observed for completely submerged explosive charges. If the waves formed are shallow water waves capable of forming tsunamis, then the upper critical depth phenomenon would be important in evaluating the magnitude of a tsunami event from other than tectonic events. As described in reference 1 the experimentally observed waves from cavities formed by explosions near the water surface are better reproduced by models solving the incompressible Navier-Stokes equations than by modeling solving the shallow water, long wave equations. The experimentally observed waves are deep water waves. The observed upper critical depth phenomenon is apparently a result of a partition of energy near the water surface, which results in high amplitude, deep water waves (of high potential and low kinetic energy) and not the shallow water waves required for tsunamis.

During the study of the upper critical depth phenomenon in the 1960's evidence of complicated and unexpected fluid flows during water cavity formation was generated by B. G. Craig and described in references 2, 3 and 4. A sphere of explosive consisting of a 0.635 cm radius XTX 8003 (80/20 PETN/Silicon Binder) explosive and a 0.635 cm radius PBX-9404 explosive was detonated at its center. The sphere was submerged at various depth in water. PHERMEX radiographs and photographs were taken with framing and movie cameras.

While the water cavity was expanding an upward water ejecta jet was generated on the axis above the water plume and a downward water jet or root was generated on the axis below the bottom of the cavity. These results were not anticipated and neither was the observation that the water cavity proceeded to close at its top and descend down into deeper water.

It was assumed that there was something unique about the explosive source that was resulting in these remarkable observations. The reactive compressible hydrodynamic numerical models available were unable to reproduce the experimental observations or suggest any possible physical mechanisms unique to explosives.

In the early 1980's experiments were being performed at the University of Arizona to simulate asteroid impacts in the ocean. The hypervelocity impact (1.25 to 6 km/sec) of various solid spherical projectiles (Pyrex or Aluminum) into water was performed by Gault and Sonett (5). Their observations were similar to those previously observed by Craig. While the water cavity was expanding, an ejecta jet was formed at the axis above the water plume and a jet or "root" emerged along the axis below the cavity. Again the water cavity appeared to close and descend into deeper water.

So it became obvious that the earlier Craig observations were not caused by some unique feature of generation of the cavity by an explosion.

To improve the photographic resolution and reduce the light from the air shock Sonett repeated his impact experiments under reduced atmospheric pressure.

Much to everyone's surprise when the pressure was reduced from one to a tenth atmosphere, the ejecta jet and the root did not occur and the water cavity expanded and collapsed upward toward the surface. This was what had been expected to occur in both the earlier Craig experiments and the projectile impacts.

So it was evident that the atmospheric pressure and the pressure differences inside and outside the water plume above the water surface was the cause of the formation of the jet, the root and the cavity closure and descent into deeper water.

Figure 1 shows the Gault and Sonett results for a 0.25 cm diameter aluminum projectile moving at 1.8 km/sec impacting water at one atmosphere (760 mm), at 130 mm air pressure, and at 16 mm air pressure. Figure 2 shows the Gault and Sonett results for a 0.635 cm diameter aluminum projectile moving at 2.5 km/sec impacting water at one atmosphere (760 mm) and a 0.3175 cm diameter projectile moving at 2.32 km/sec impacting water at 16 mm air pressure.

Professor Kedrinskii at the Russian Institute for Hydrodynamics was also studying the generation of water cavities from exploding bridge wires (6). He was observing the formation of jets and roots as the water cavity expanded similar to those observed by Craig using explosives and by Gault and Sonett using projectiles. After we showed him the effect of reduced atmospheric pressure, he proceeded to repeat his exploding bridge wire experiments under reduced pressure. He observed that the jets and roots did not form when the atmospheric pressure was reduced to 0.2 atmosphere.

Figure 3 shows the Kedrinskii results for a exploding bridge wire in water at one atmosphere and at 0.2 atmosphere air pressure.

The different behavior of the water cavity as it expanded when the atmospheric pressure was reduced from one atmosphere to less than a third of an atmosphere is independent of the method used to generate the cavity such as a high explosive charge, an exploding bridgewire or a hypervelocity projectile impact.

These remarkable experimental observations resisted all modeling attempts for over 25 years. The numerical simulations could not describe the thin water ejecta plumes formed above the cavity or the interaction with the atmosphere on the outside of the ejecta plume and the pressure inside the expanding cavity and plume.

## COMPRESSIBLE NAVIER STOKES MODELING

The projectile impact and explosive generated water cavity generation was modeled with the recently developed full Navier-Stokes AMR (Adaptive Mesh Refinement) Eulerian compressible hydrodynamic code called SAGE (7, 8, 9, 10, 11) which includes the effects of gravity. The continuous adaptive mesh refinement permits the following of shocks and contact discontinuities with a very fine grid while using a coarse grid in smooth flow regions. This allows the code to devote the bulk of the computing resources to those areas where they are needed most. It can resolve the water plume and the pressure gradients across the water plume and follow the generation of the water ejecta jet and root.

Figure 4 shows the calculated density profiles for a 0.25 cm diameter aluminum projectile moving at 2.0 km/sec impacting water at five atmosphere air pressure.

Figure 5 shows the calculated density profiles for a 0.25 cm diameter aluminum projectile moving at 2.0 km/sec impacting water at one atmosphere air pressure.

Figure 6 shows the calculated density profiles for a 0.25 cm diameter aluminum projectile moving at 2.0 km/sec impacting water at 0.1 atmosphere air pressure.

Figure 7 shows the calculated water profiles for a 0.25 cm diameter PBX-9404 explosive sphere detonated at its center half submerged in water at one atmosphere air pressure.

The computer animations are available in the file sonnet.zip at
http://t14web.lanl.gov/Staff/clm/tsunami.mve/tsunami.htm
as hyperlink "Water Cavity Generation by Projectiles and Explosives".

The experimental observations were reproduced as the atmospheric pressure was varied. When the atmospheric pressure was increased the difference between the pressure outside the ejecta plume above the water cavity and the decreasing pressure inside the water plume and cavity as it expanded resulted in the ejecta plume converging and colliding at the axis forming a jet of water proceeding above and back into the bubble cavity along the axis. The jet proceeding back thru the bubble cavity penetrates the bottom of the cavity and forms the root observed experimentally. The complicated bubble collapse and resulting descent into deeper water was also numerically modeled for the one atmosphere and higher cases.

## CONCLUSIONS

In the late 1960's and early 1970's, B. G. Craig at the Los Alamos National Laboratory reported observing the formation of ejecta jets and roots by bubbles generated by small spherical explosives detonated near the water surface while the gas cavity was expanding.

The hypervelocity impact (1.25 to 6 km/sec) of projectiles into water was studied at the University of Arizona in the early 1980's by Gault and Sonett. They observed quite different behavior of the water cavity as it expanded when the atmospheric pressure was reduced from one to a tenth atmosphere. Above about a third of an atmosphere, a jet of water formed above the expanding bubble and a root developed below the bottom of the bubble. They did not occur for atmospheric pressures below a third of an atmosphere.

Similar results were observed in the middle 1980's by Kedrinskii at the Institute of Hydrodynamics in Novosibirsk, Russia when the water cavity was generated by exploding bridge wires with jets and roots forming for normal atmospheric pressure and not for reduced pressures.

During the last decade a compressible Eulerian hydrodynamic code called SAGE has been under development by the Los Alamos National Laboratory and Science Applications International (SAIC) which has continuous adaptive mesh refinement (AMR) for following shocks and contact discontinuities with a very fine grid.

A version of the SAGE code that models explosives called NOBEL has been used to model the experimental geometries of Sonett and of Craig. The experimental observations were reproduced as the atmospheric pressure was varied. When the atmospheric pressure was increased the difference between the pressure outside the ejecta plume above the water cavity and the decreasing pressure inside the water plume and cavity as it expanded resulted in the ejecta plume converging and colliding at the axis forming a jet of water proceeding above and back into the bubble cavity along the axis. The jet proceeding back thru the bubble cavity penetrated the bottom of the cavity and formed the root observed experimentally. The complicated bubble collapse was numerically modeled.

Now that a code is available that can describe the experimentally observed features of projectile interaction with the ocean, we have a tool that can be used to evaluate impact landslide, projectile or asteroid interactions with the ocean and the resulting generation of tsunami waves.

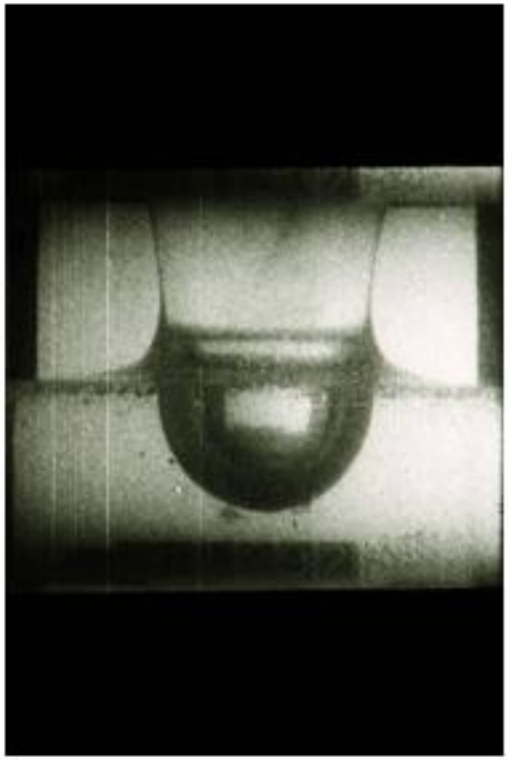
## REFERENCES


1. Charles L. Mader, **Numerical Modeling of Water Waves,** University of California Press, Berkeley, California (1988).
2. Charles L. Mader, "Detonations Near The Water Surface", Los Alamos Scientific Laboratory report LA-4958 (1972).
3. Charles L. Mader, **Numerical Modeling of Detonations,** University of California Press, Berkeley, California (1979).
4. Bobby G. Craig, "Experimental Observations of Underwater Detonations Near the Water Surface", Los Alamos Scientific Laboratory report LA-5548-MS (1972).
5. Donald E. Gault and Charles P. Sonett "Laboratory Simulation of Pelagic Asteroid Impact: Atmospheric Injection, Benthic Topography, and the Surface Wave Radiation Field", Geological Society of America, Special Paper 190, pages 69-92 (1982).
6. Valery Kedrinskii, private communication (1985).
7. M. L. Gittings, "1992 SAIC's Adaptive Grid Eulerian Code", Defense Nuclear Agency Numerical Methods Symposium, 28-30 (1992).
8. R. L. Holmes, G. Dimonte, B. Fryxell, M. L. Gittings, J. W. Grove, M. Schneider, D. H. Sharp, A. L. Velikovich, R. P. Weaver and Q. Zhang, "Richtmyer-Meshkov Instability Growth: Experiment, Simulation and Theory", J. Fluid Mech. 389, 55-79 (1999).
9. R. M. Baltrusaitis, M. L. Gittings, R. P. Weaver, R. F. Benjamin and J. M. Budzinski, "Simulation of Shock-Generated Instabilities," Phys. Fluids, 8, 2471-2483 (1996).
10. Charles L. Mader, John D. Zumbro and Eric N. Ferm, "Proton Radiographic and Numerical Modelng of Colliding Diverging PBX-9502 Detonations," Twelfth International Symposium on Detonation, August 11-16, 2002, San Diego, California. Also at http://t14web.lanl.gov/Staff/clm/prad77/prad77.htm.
11. Charles L. Mader, Michael L. Gittings, "Modeling the 1958 Lituya Bay Mega Tsunami, II," Science of Tsunami Hazards, Volume 20, Number 5, pages 241-250 (2002). Also in the file litavi.zip at http://t14web.lanl.gov/Staff/clm/tsunami.mve/tsunami.htm hyperlink "Lituya Impact Landslide".


**Los Alamos National Lab Contribution LA-UR-02-7735**

760 mm Air

130 mm Air



16 mm Air

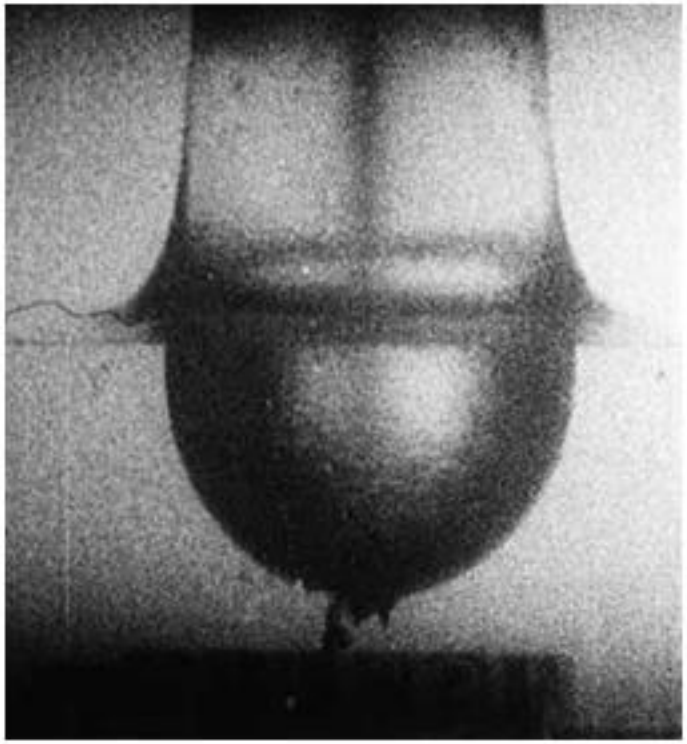


Figure 1. Gault and Sonnet results for a 0.25 cm diameter Aluminum Projectile moving at 1.8 km/sec impacting water.

760 mm Air – Al Projectile at 2.5 km/sec

16 mm Air – Pyrex Projectile at 2.32 km/sec

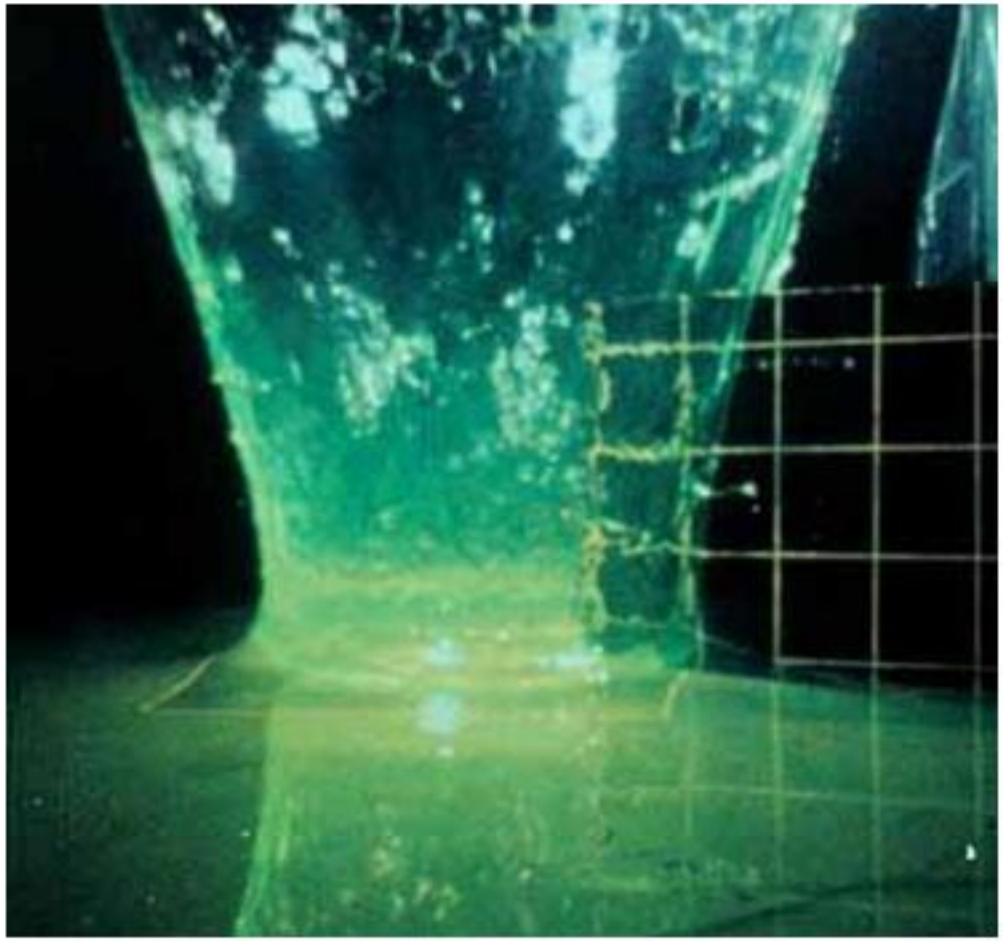
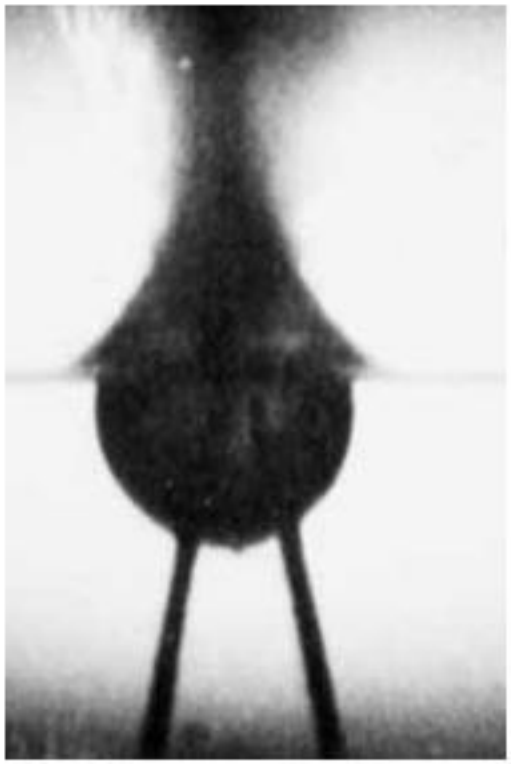
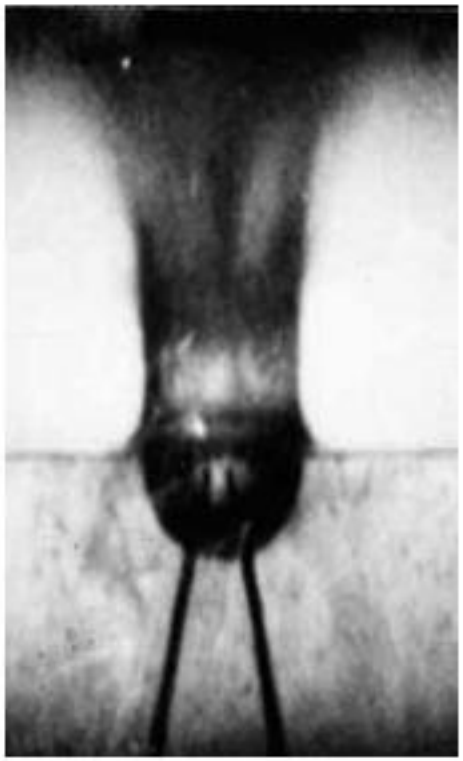


Figure 2 – Gault and Sonnet results for a 0.635 cm diameter Aluminum Projectile moving at 2.5 km/sec and for a 0.3175 diameter Pyrex Projectile moving at 2.32 km/sec

760 mm Air



150 mm Air



150 mm Air

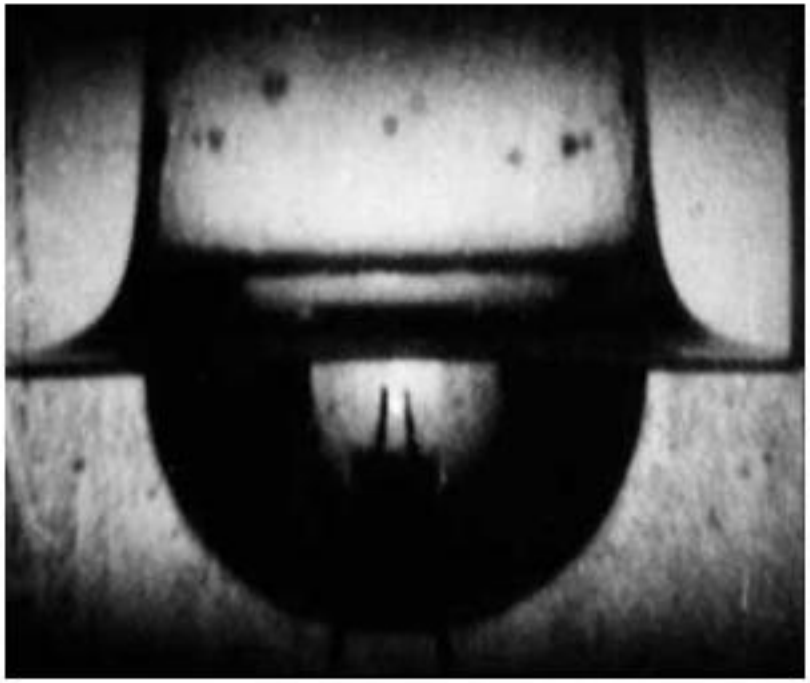


Figure 3. Kedrinskii results for an Exploding Bridge Wire in Water at 760mm and 150 mm Air Pressure.

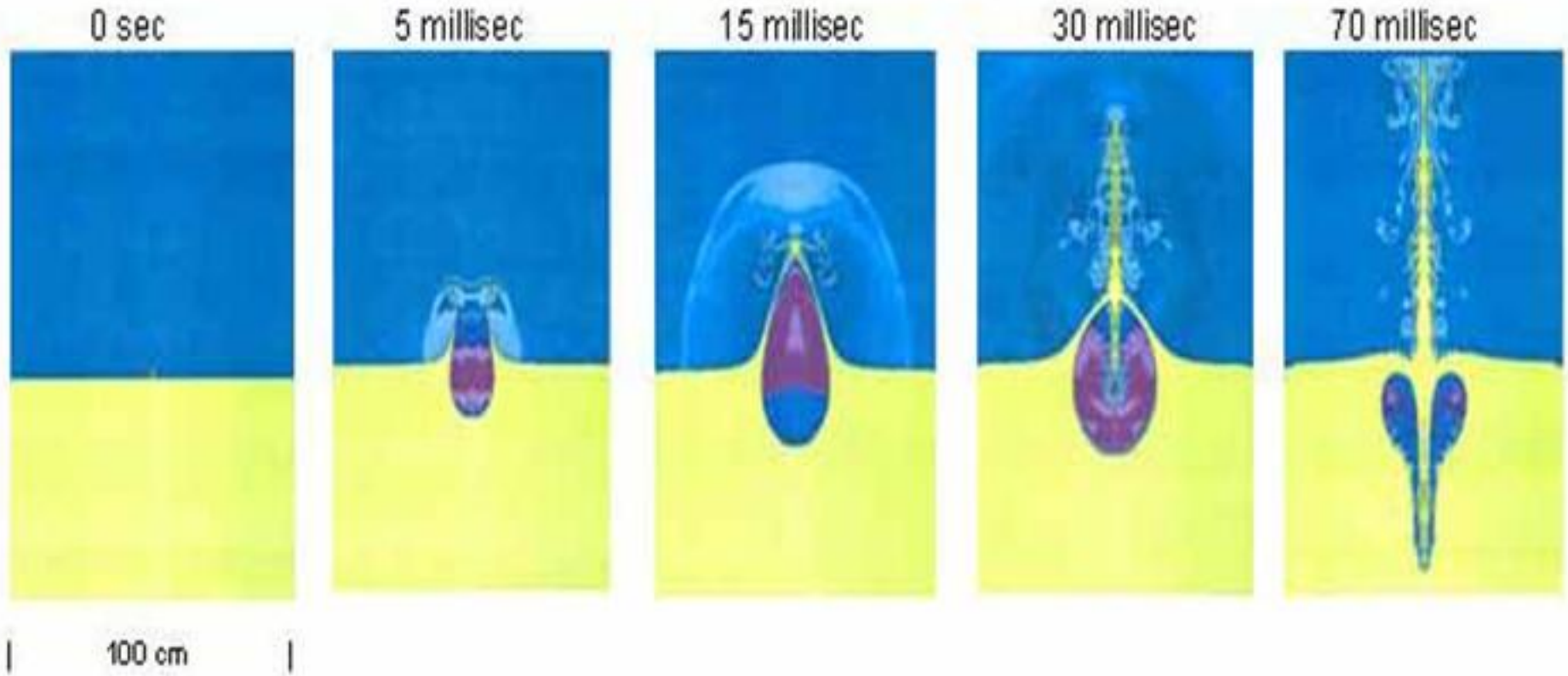



Figure 4. Density Profiles for a 0.25 cm dia Al Projectile Moving 2.0 km/sec Impacting water In Five Atmosphere Air.

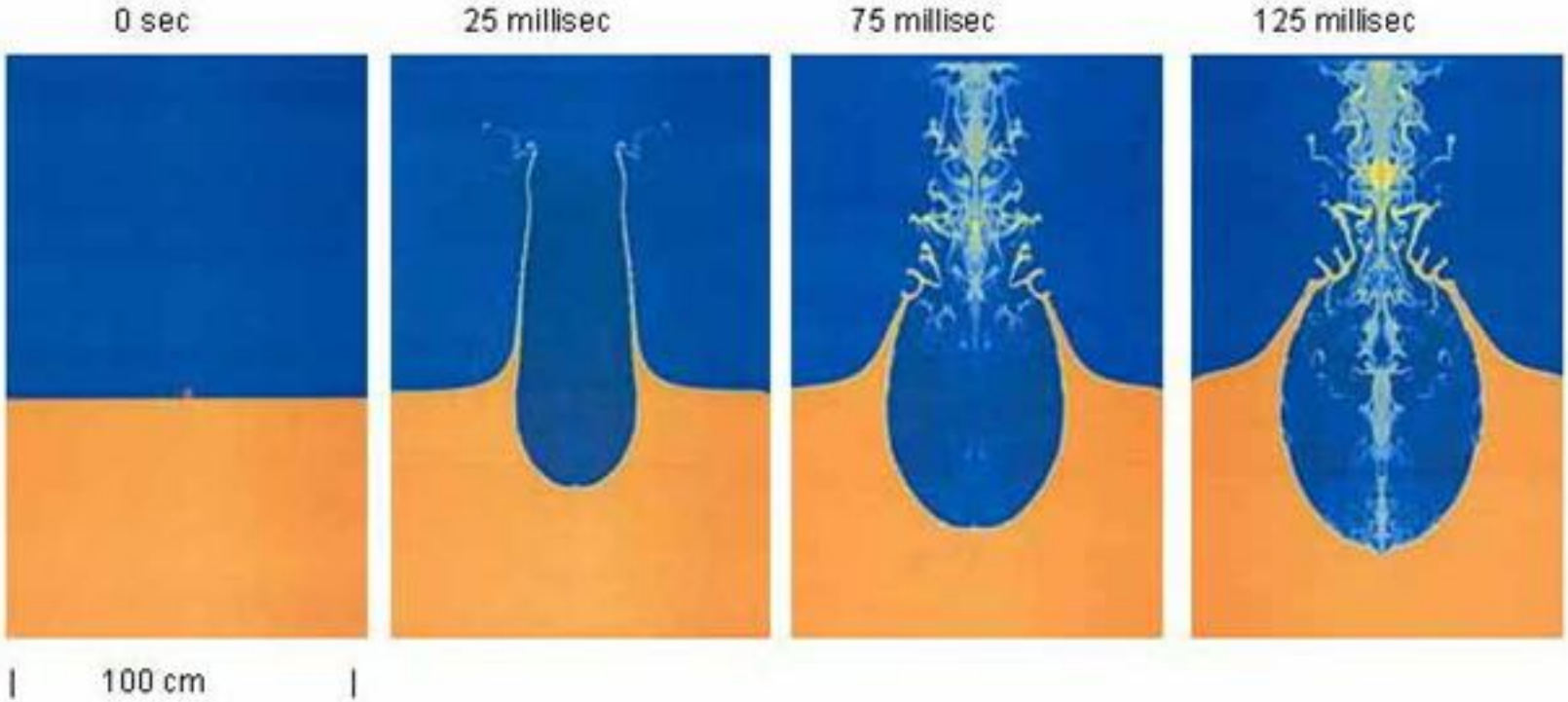



Figure 5. Density Profiles for a 0.25 cm dia Al Projectile Moving at 2.0 km/sec Impacting Water at One Atmosphere Air Pressure.

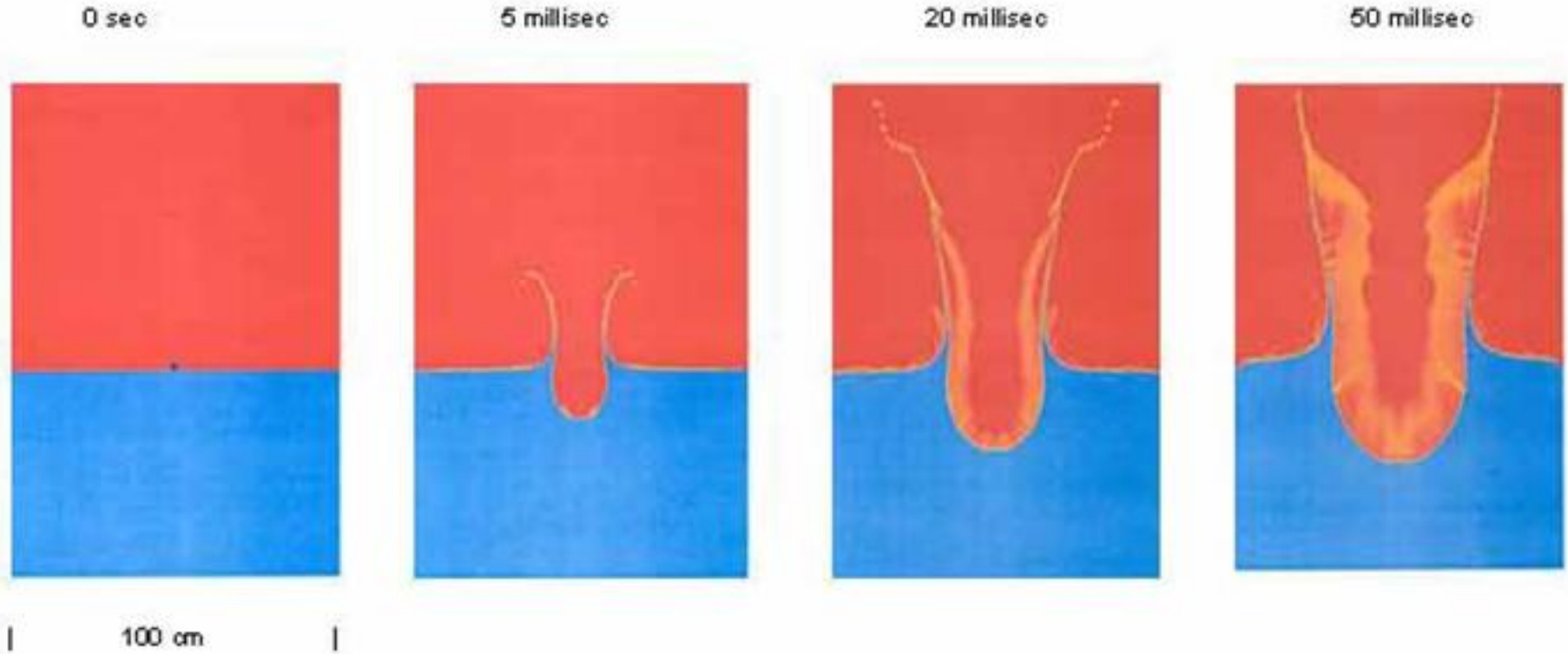



Figure 6. Density Profiles for a 0.25 cm Dia Al Projectile Moving at 2.0 km/sec Impacting Water in Air at 76 mm (0.1 atmos) Pressure.

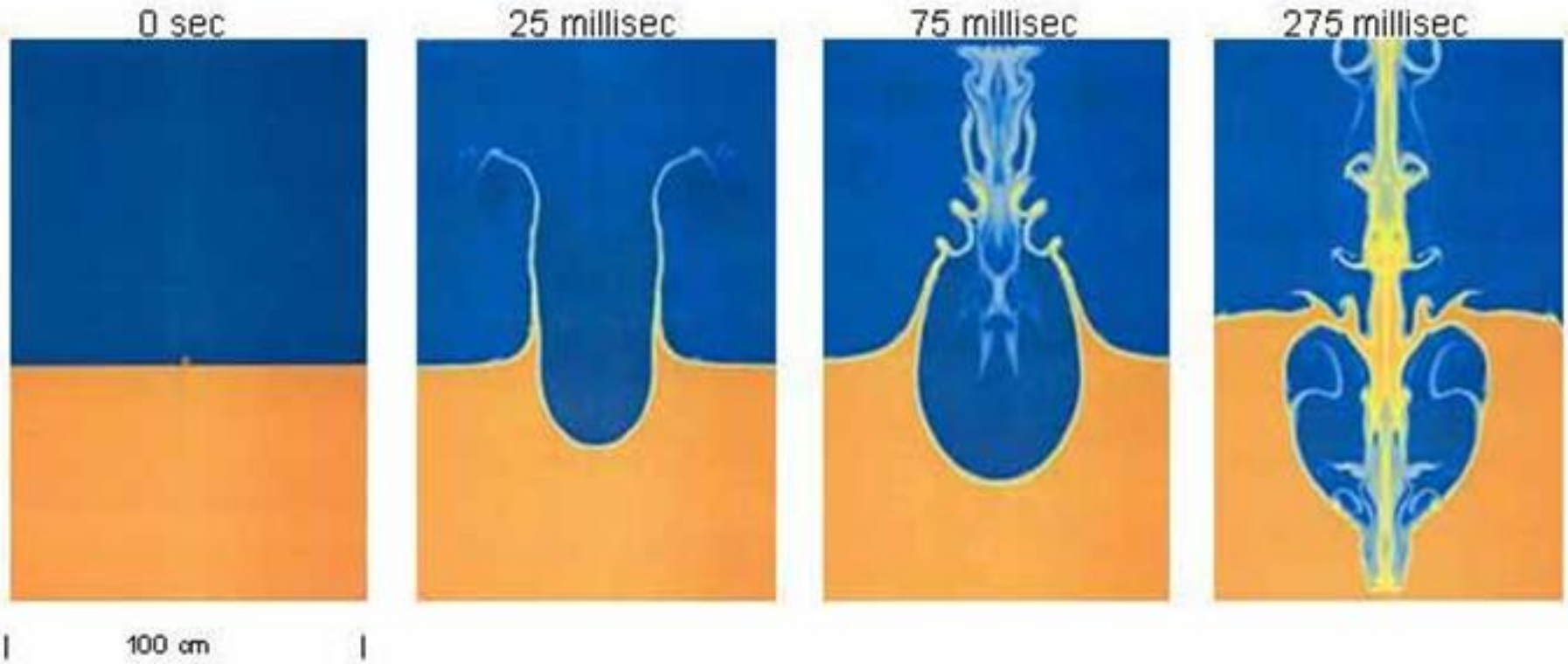



Figure 7. Density Profiles for a 0.25 cm Dia PBX-9404 Explosive Sphere Detonated at its Center and Half Submerged in Water at One Atmosphere Air Pressure.