CONF-810602--2

LA-UR-81-203

TITLE: DETONATION-WAVE INTERACTIONS

MASTER

AUTHOR(S): Charles L. Mader

SUBMITTED TO: 7th Symposium (International) on Detonation

University of California

LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545
An Affirmative Action/Equal Opportunity Employer

UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

DETONATION-WAVE INTERACTIONS

Charles L. Mader
Los Alamos National Laboratory
Los Alamos, New Mexico

The interaction of laterally colliding, diverging, cylindrical detonation waves in PBX-9404 has been studied using the radiographic machine PHERMEX and the two-dimensional, reactive Lagrangian hydrodynamic code 2DL. The experimentally observed flow could be numerically reproduced using the Forest Fire heterogeneous shock initiation burn model which permits realistic numerical simulation of the burning region of regular and diverging detonation waves, and the interacting detonation waves undergoing regular and Mach reflection.

The interaction of two, three, and five colliding, diverging spherical detonation waves in PBX-9404 has been numerically modeled using the three-dimensional, reactive Eulerian hydrodynamic code 3DE. The size and magnitude of the high pressure double, triple, quadruple, and quintuple interactions depends significantly upon the number and relative locations of initiators.

The initiation of propagating detonation in the insensitive explosive PBX-9502 by triple shock-wave interaction resulting from three initiators has been studied using the 3DE code with Forest Fire kinetics.

CYLINDRICAL DETONATION WAVE INTERACTIONS

The interaction of shock waves in aluminum to form both regular and Mach shock reflections has been studied experimentally by Al'Tshuler et al. (1) and reproduced using the numerical two-dimensional Lagrangian hydrodynamic code 2DL, by Mader (2). The calculated Mach stems in aluminum were not well described by the usual simple three-shock model. The stems have significant curvature and are better described by a multiple-shock process with a slip region rather than a three-shock process with a slip plane. The calculated growth angle of the aluminum Mach stem increased with increasing collision angle up to near 90°, where a sharp discontinuity occurs.

Attempts (2) at studying colliding detonation waves of homogeneous explosives such as nitromethane with resolved reaction zones were unsuccessful because the orders of magnitude change in reaction zone thickness from the regular reaction zone to the Mach stem reaction zone could not be resolved numerically.

Gardner and Wackerle (3), using radiographic and rotating mirror camera techniques, studied the interaction of plane detonation waves of Composition B, PBX-9404, Baratol, and nitromethane. They observed that Mach stems and reflected shocks displayed substantial curvature and anomalous density regions and concluded that their observations could not be reproduced using the usual three-shock models.

Lamborn and Wright (4), using streak cameras and ionization probes, determined the rate of growth of a Mach stem formed between two plane intersecting detonation waves in Composition B at various angles of incidence. The three-shock model predicted growth angles about four times larger than observed. They concluded that the theory needed to include the effect of the reaction zone, the Taylor wave, and the signal emanating from where the waves first intersect. They also concluded that two-dimensional numerical hydrodynamics was required. They performed such a calculation with encouraging results but the crude mesh used prevented a detailed comparison with the experimental data.

A series of radiographic studies was performed by D. Venable (5) in 1969 of two laterally colliding, diverging cylindrical detonation waves in PBX-9404 (94/3/3 HMX/nitrocellulose/Tris-β-chloroethyl phosphate at 1.844 g/cm³) using the PHERMEX machine (6). The experimental arrangement is shown schematically in Fig. 1. Line wave generators served to initiate these waves. The radiograph at 11.16 μs after arrival of the generator shock wave is shown in Fig. 2. Measurements have been made of the space-time history of the detonation wave and the interaction region which starts with regular reflection and subsequently develops into Mach reflection. This interaction range covers angles of incidence, with respect to the plane of symmetry, from zero to about 85°; the Mach wave is born at about 50°. The detonation wave trajectory yielded a wave velocity of 8.745 ± 0.016 mm/μs, roughly 1% lower than the 8.80 that is normally taken for the velocity, D, of a plane detonation wave in PBX-9404 of the same density. It is noted that this difference is also roughly the limit of our present capability to make a velocity measurement, so that we are only able to say that the detonation wave velocity is nearly constant. On the other hand, it is clear that the Mach wave velocity beginning at its point of origin starts with a velocity, in excess of 12 mm/μs, considerably greater than that of the detonation wave and slows down, asymptotically approaching the detonation wave velocity.

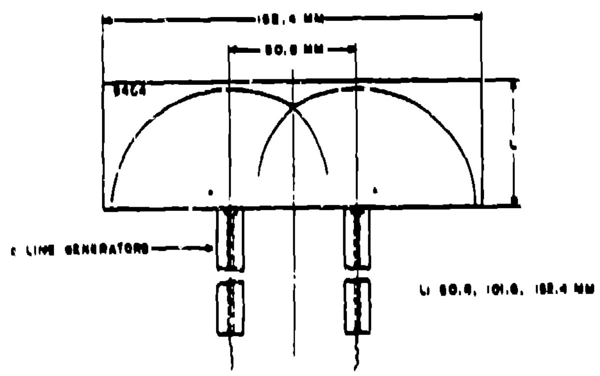


Fig. 1 - Schematic of experimental setup.

The results are similar to those reported previously in that the Mach stems are substantially curved with anomalous density regions. Numerical simulation of the experiments appeared hopeless as long as the problem of resolving the reaction zone could not be solved or circumvented.

The development of the Forest Fire model (7) of shock initiation of heterogeneous explosives has furnished us with a technique for achieving a realistic numerical simulation of the burning region of the regular detonation wave and the Mach stem.

The Forest Fire model can describe the decomposition that occurs from hot spots formed by shock interactions with density discontinuities in heterogeneous explosives which apparently dominate the detonation wave propagation process in such explosives. It has been used to describe the passage of a heterogeneous detonation wave around a corner and along metal surfaces (7). It has been used to model the failure or propagation of heterogeneous detonation waves (7) which depend upon the interrelated effects of the wave curvature and the shock sensitivity of the explosive. The Forest Fire model is, therefore, an obvious choice for numerically simulating the important features of the burning regions of interacting detonation waves.

The finite difference analogs of the Lagrangian equations of motion of a compressible fluid that were used in the

Fig. 2 - PHERMEX radiograph 1037 μs after arrival of generator shock wave.

2DL code are decribed in Appendix B of Ref. 7. The PBX-9404 equation of state and the Forest Fire constants used are described in Chapter 4 of Ref. 7.

The calculations were performed using 6400 cells each 2.0 mm square. The volume viscosity constant (7) used was 3.0. The line initiation was simulated by starting the calculation with a four-cell region of PBX-9404 decomposed and with its CJ pressure.

Figure 3 shows the calculated density contours with a 0.02-cc/g interval at the same time as the radiographs in Fig. 2. Also shown is the trace of the radiograph profile. The pressure contours are shown in Fig. 4 with a 20-kbar interval.

To study the effect of multi-initiator explosive initiation on the explosive acceleration of a thin metal plate, the laterally colliding PBX-9404 detonations were permitted to run for 6.2 cm and then interact with a 0.4-cm-thick copper plate as shown in Fig. 5. A series of shocks and rarefactions travel back and forth in the metal plate, resulting in a very irregular free-surface profile.

The flow resulting from laterally colliding, diverging cylindrical detonation waves in PBX-9404 have been numerically reproduced using the Forest Fire explosive burn model in a two-dimensional finite-difference Lagrangian hydrodynamic code. The observed complicated nature of the Mach stem is also reproduced by the calculations.

These results suggest that detonation waves resulting from initiation by multiple detonators can be modeled by three-dimensional hydrodynamic codes using the Forest Fire model to describe the heterogeneous detonation wave propagation.

SPHERICAL DETONATION WAVE INTERACTIONS

The Eulerian equations of motion are most useful for numerical solution of highly distorted flow. The two-dimensional, reactive, Eulerian computer code 2DE is described in detail in Ref. 7. The unique feature of the technique used in 2DE is the mixed equation-of-state treatments and the use of the associated state values in the mixed cells in the mass movement across cell boundaries. This permits solution of interface flow within the cell resolution and an accuracy of state values almost as good as one can obtain with Lagrangian treatments. This requires keeping track of the mixed cell properties and rather complicated logic to follow the mass movement.

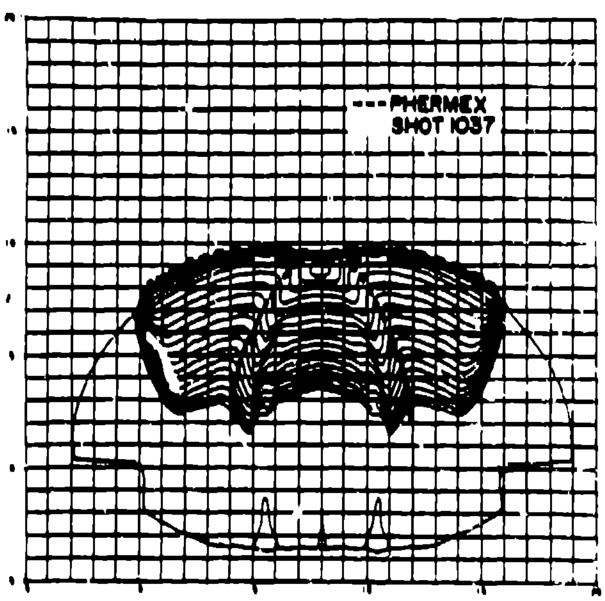


Fig. 3 - The calculated isopycnic contours at 11.2 μs. The contour interval is 0.02 g/cc. The shock wave profiles from shot 1037 are shown.

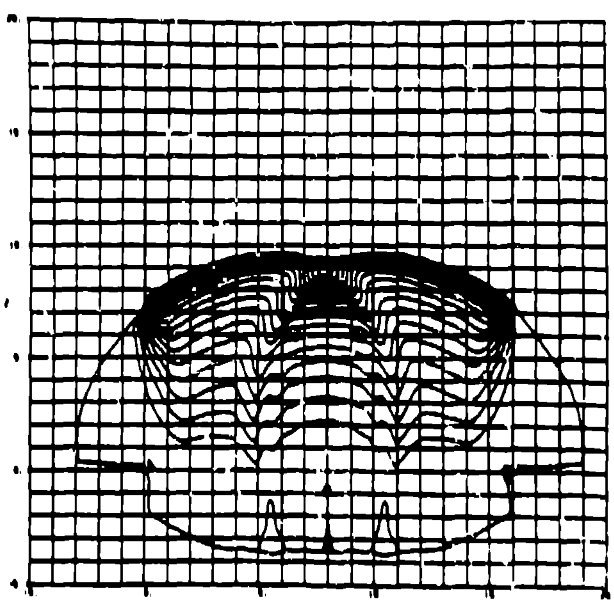


Fig. 4 - The calculated isobar contours at 11.2 μs. The contour interval is 20 kbar.

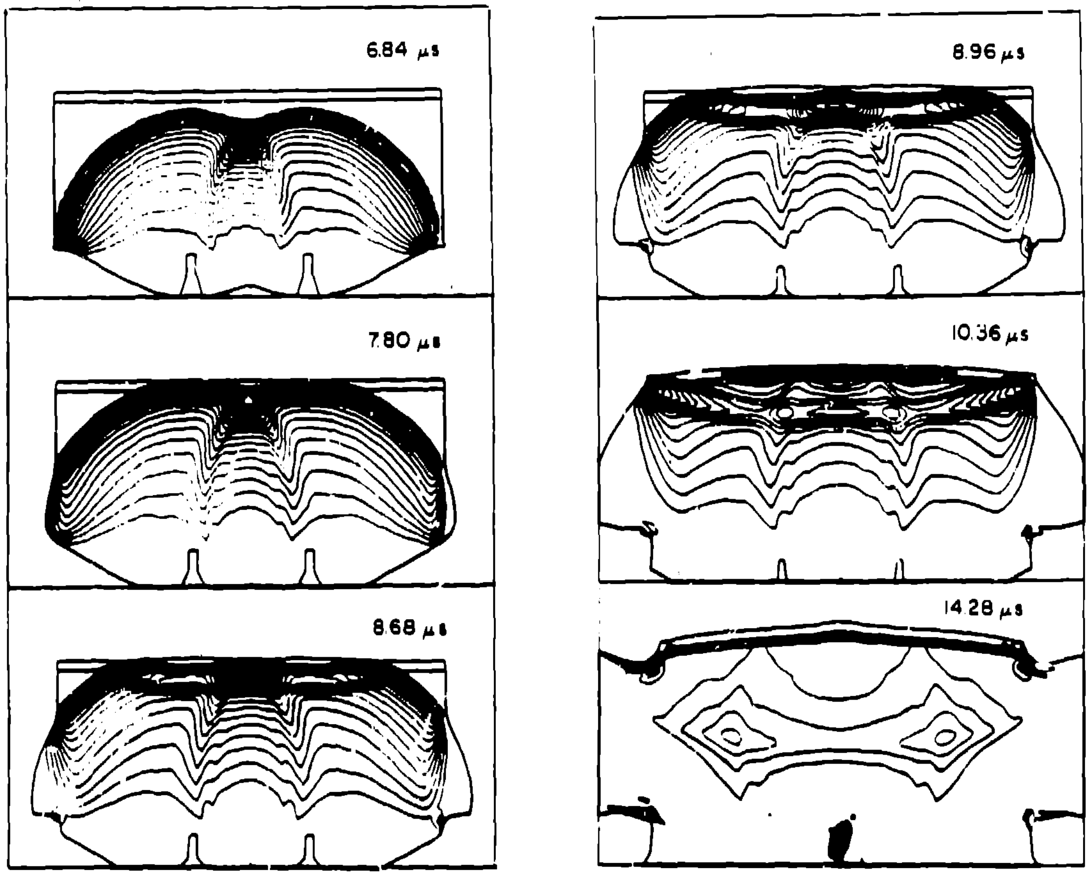


Fig. 5 - The calculated isobar contours for two cylindrical diverging detonations, initially 5.0 cm apart, interacting with a 0.4-cm copper plate after 6.2 cm of run.

The first three-dimensional Eulerian hydrodynamic code used the particle-in-cell technique and was described by Gage and Mader (8) in 1966. It was used to study the closure of a cubical hole in nitromethane by a shock wave propagating up one side of the cube. The resulting three-dimensional hydrodynamic hot spot was described by the calculation. The first three-dimensional continuous Eulerian code was described by Johnson (9) in 1967. A three-dimensional incompressible calculation was used to study flow around buildings by Hirt and Cook (10) in 1972. Compressible three-dimensional calculations of blast loading and channel flow are described in Refs. 11, 12, and 13. The first three-dimensional Lagrangian hydrodynamic code was described by Wilkins (14) in 1970. While various three-dimensional hydrodynamic codes have been in existence for over a decade, they have been little used because most problems of interest required more resolution than one could obtain with the computer hardware available.

The new CRAY computer, with its two million words of memory, permits one to have approximately 130,000 cells or a cube with 50 cells on each side. While this is inadequate for most problems, it will permit us to study some problems of interest to reactive fluid dynamics.

We have constructed a three-dimensional, reactive, multicomponent Eulerian hydrodynamic code called 3DE. The 3DE code uses techniques identical to those for 2DE for describing mixed cells and multicomponent equations of state, and for modeling reactive flow. The code is described in Ref. 15.

The geometry studied is shown in Fig. 6. Initiator cubes of 4 by 4 by 4 cells are placed in a cube of PBX-9404 with continuum boundaries on its sides. The indices i, j, and k designate the positions of the x-, y-, and z-coordinates. The total cube height is k of 31, i is 29, and j is 25, for a total of 22,475 cells. The initiator cubes were

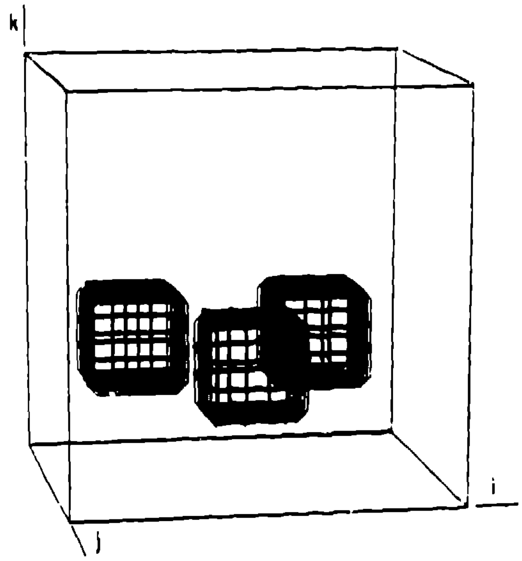


Fig. 6 - Schematic of an explosive cube with three rectangular initiators.

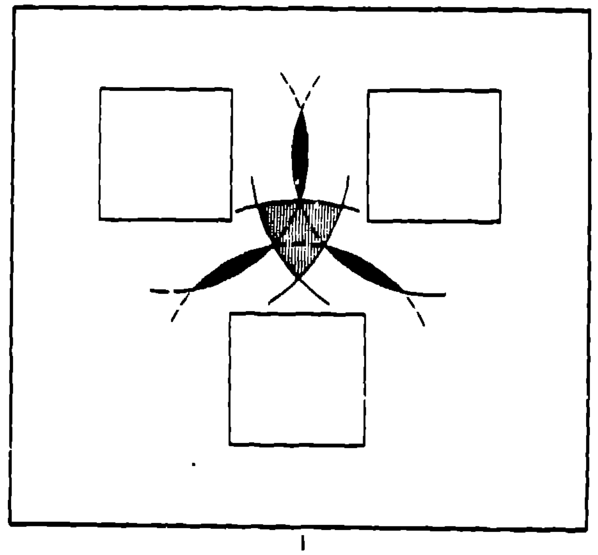


Fig. 7 - The double and triple detonation wave interactions from three symmetric detonators. The dashed lines and dark regions show double wave interaction. The solid lines and dotted region show triple wave interaction.

initially PBX-9404 with an initial density of 3.0 g/cm³, energy of 0.05 Mbar-cc/g, and pressure of 640 kbar. To initiate prompt propagating, diverging detonation, the initial conditions of the initiators must be sufficient to shock the surrounding undecomposed PBX-9404 to several hundred kilobars. The computational cell size used was 0.114 cm and the time step was 0.02 μs.

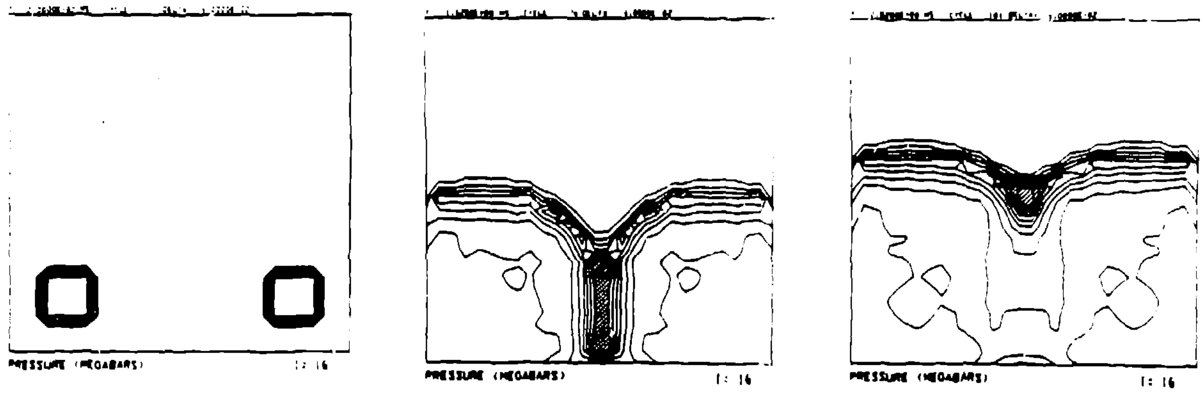
The expected wave interactions are sketched in Fig. 7. The sketch shows what would be expected if three spherically diverging waves interacted as pairs and as triplets. The dashed lines show the waves just after double wave interaction has occurred and the dark regions show the areas of double wave interaction. The solid lines and dotted regions show the waves after triple wave interaction has occurred.

The understanding of results from three-dimensional calculations requires considerable effort if one is to obtain a three-dimensional picture from the usual one- and two-dimensional presentations of data. The best technique for studying the results is to construct a three-dimensional model, as described in Ref. 8, by making clear prints of cross sections of the cube and mounting them to scale in grooved Lucite boxes. Computer-generated color movies with rotating perspective views are also effective in presenting the three-dimensional flow. Since models or movies cannot be presented in a paper, we must examine the results of the flow by studying cross sections in the i, j, and k planes, holding one axis constant at a particular time of interest, or studying a perspective view of the flow.

To compare with the two cylindrical diverging detonation waves previously described, calculations were performed for two interacting, spherically diverging detonation waves. The isobaric cross-sectional plots are shown in Fig. 8. The initiator centers are 1.8 cm apart. The pressure interval is 50 kbar. The pressure region greater than 350 kbar is shown crosshatched. Because the plane wave CJ pressure of PBX-9404 is 365 kbar and the diverging effective CJ pressure is approximately 300 kbar, the regions above 350 kbar must result from regular or Mach reflection. The regular and Mach stems formed by colliding, diverging detonations are shown. The Mach stem becomes larger but of lower pressure as it proceeds through the explosive.

The plots are shown in Fig. 9 for three symmetric initiators whose top two centers are 1.8 cm apart and 1.75 cm from the bottom initiator. At the center between the three initiators, a triple wave interaction occurs that gives a triple wave regular or triple wave Mach reflection, depending upon the angle of interaction of the three waves.

The plots are shown in Fig. 10 for five initiators initially positioned as



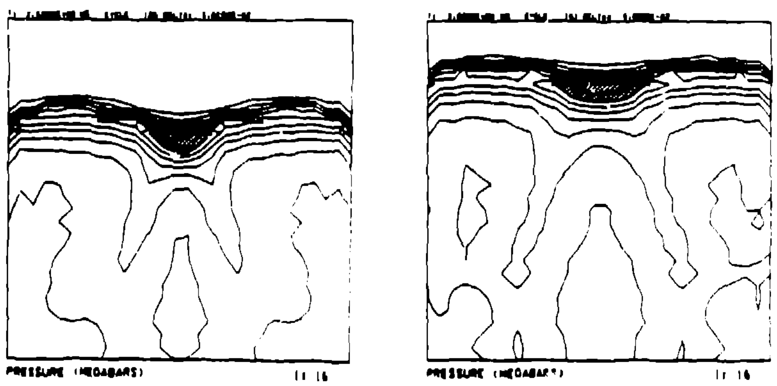


Fig. 8 - The isobar cross sections for cell layer I of 16 for two initiators in PBX-9404. The pressure contour interval is 50 kbar. The regions of regular and Mach reflection above 350 kbar are crosshatched. The times are 0.0, 1.52, 2.02, 2.52, and 3.02 μs.

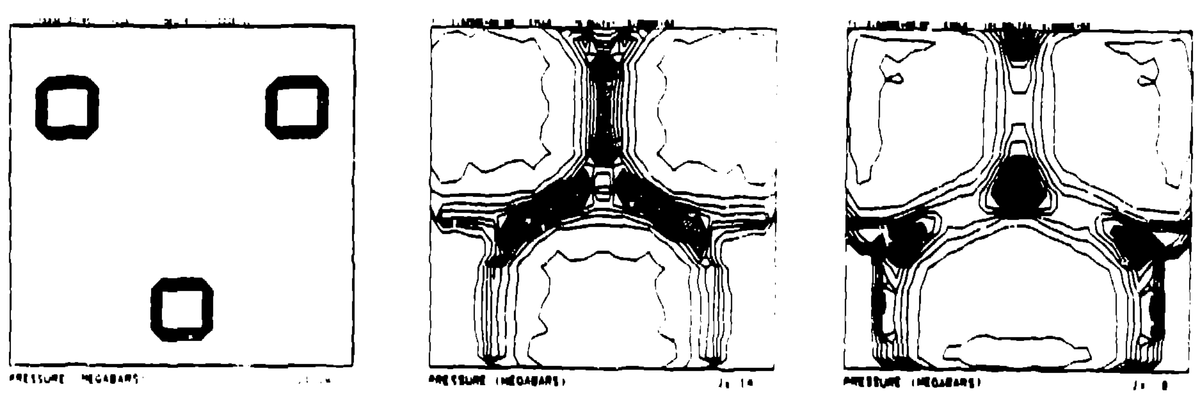


Fig. 9 - The isobar cross sections for cell layer J of 14 at 1.52 μs and J of 8 at 2.02 μs for three initiators in PBX-9404. The pressure contour interval is 50 kbar. The regions of double and triple reflection are crosshatched above 350 kbar and shaded above 600 kbar.

shown in the figure. The top cell centers are 1.8 cm apart and 1.75 cm from the bottom cell center. The regions whose pressures are greater than 350 kbar are crosshatched and greater than 600 kbar are shaded. The quadruple and quintuple wave interactions give detonation pressures as high as 1 Mbar.

The three-dimensional Eulerian hydrodynamic computer code 3DE has been used to examine the flow resulting from the interaction of two, three, and five spherically diverging detonation waves. The size and magnitude of the high pressure double, triple, quadruple, or quintuple wave interactions depend significantly upon the number and initial

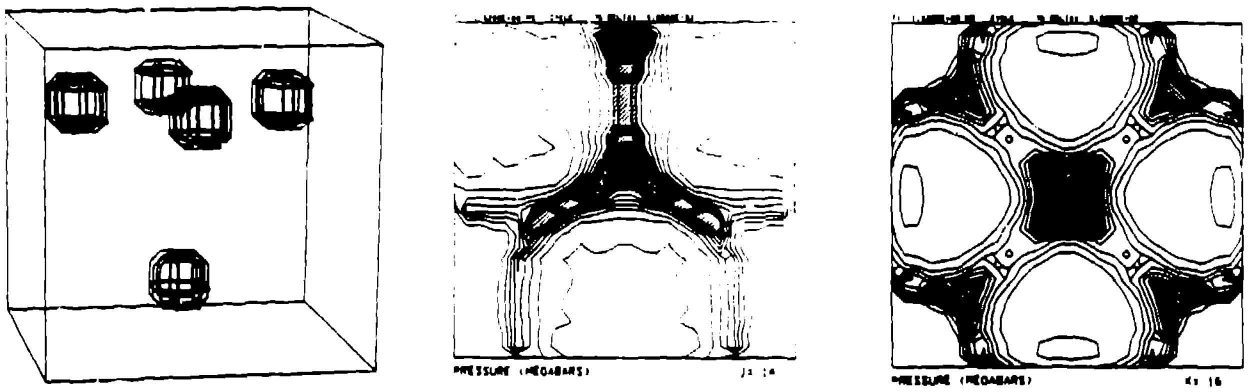


Fig. 10 - The isobar cross section for cell layer J of 14 and layer K of 16 at 1.52 μs for five initiators in PBX-9404 initially positioned as shown in the perspective view. The pressure contour interval is 50 kbar. The regions of double, triple, quadruple, and quintuple reflection are crosshatched above 350 kbar and shaded above 600 kbar.

relative positions of the initiators. The initiation mechanism for lower energy detonators that do not cause prompt initiation of the surrounding explosive can now be studied.

TRIPLE WAVE INITIATION OF INSENSITIVE EXPLOSIVES

The initiation of propagating, diverging detonation is usually accomplished by small conventional initiators. As the explosive to be initiated becomes more shock insensitive, the initiators must have large diameters (>2.5 cm) to be effective, or some other method must be used to achieve the required high pressure of adequate duration. We have investigated the initiation of propagating detonation in the insensitive high explosive PBX-9502 (95/5 TATB/Kel-F at 1.894 g/cm^3) by the double and triple wave interaction of shock waves formed by initiators that are too weak to initiate propagating detonation individually.

The use of multiple shock-wave interactions to initiate propagating detonation in explosives was experimentally studied by Goforth (16).

The initiation of propagating detonation in sensitive (PBX-9404) and insensitive (PBX-9502 and X0219) explosives by hemispherical initiators was studied experimentally and modeled numerically in Ref. 17. Large regions of partially decomposed explosive were observed to occur even when large initiators were used to initiate propagating detonation in insensitive explosives.

The geometry studied is shown in Fig. 6. Three initiator cubes of 7 by 7 by 7 cells are placed symmetrically in a cube of PBX-9502 with continuum boundaries on its sides. The centers of the initiator cubes were 1.6 cm apart and 1.09 cm from the bottom of the cube. The initiator cubes were initially decomposed PBX-9502 with an initial density of 2.5 g/cm^3 and pressure of 245 kbar. This will send a diverging shock wave into the surrounding PBX-9502 of about 100 kbar. The other dimensions of the calculation were identical to those described previously for PBX-9404.

The pressure from the diverging double-wave interaction in inert PBX-9502 is about 200 kbar and from the triple wave interaction is about 300 kbar.

The calculated perspective pressure and mass fraction contours for two initiators are shown in Fig. 11 and for three initiators in Fig. 12.

While two initiators result in a double wave interaction that results in considerable decomposition, it does not result in a propagating detonation.

Three initiators fail to initiate propagating detonation at the double interaction points, but do at the triple wave interaction region. The higher pressure of the triple wave interaction region results in a shorter distance of run to detonation. The detonation can be maintained long enough to become a propagating, diverging detonation.

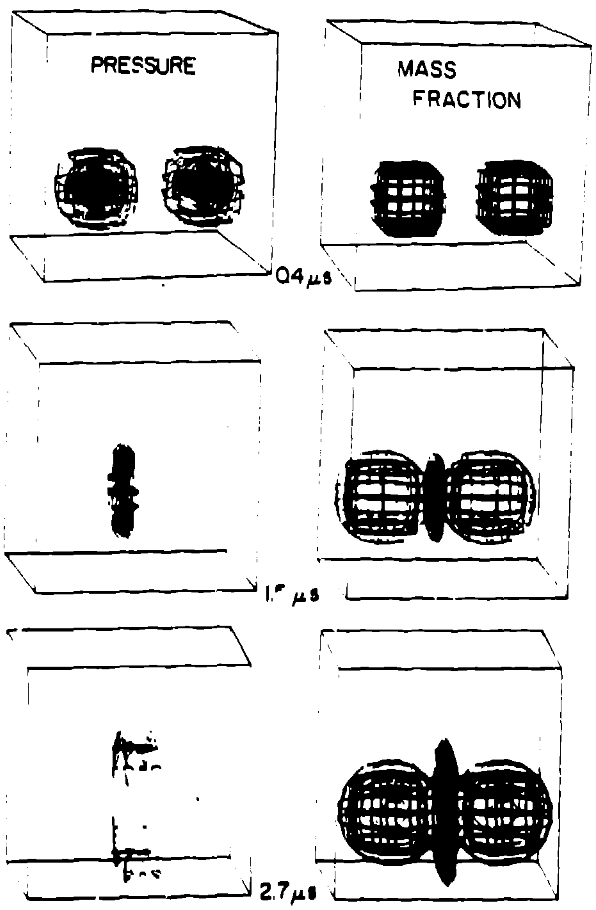


Fig. 11 - The three-dimensional perspective pressure and mass fraction contours for two initiators in PBX-9502. The pressure contours are shown for 200, 150, and 100 kbar at 0.4, 1.5, and 2.7 μs. The mass fraction contours are 0.8 and 0.5.

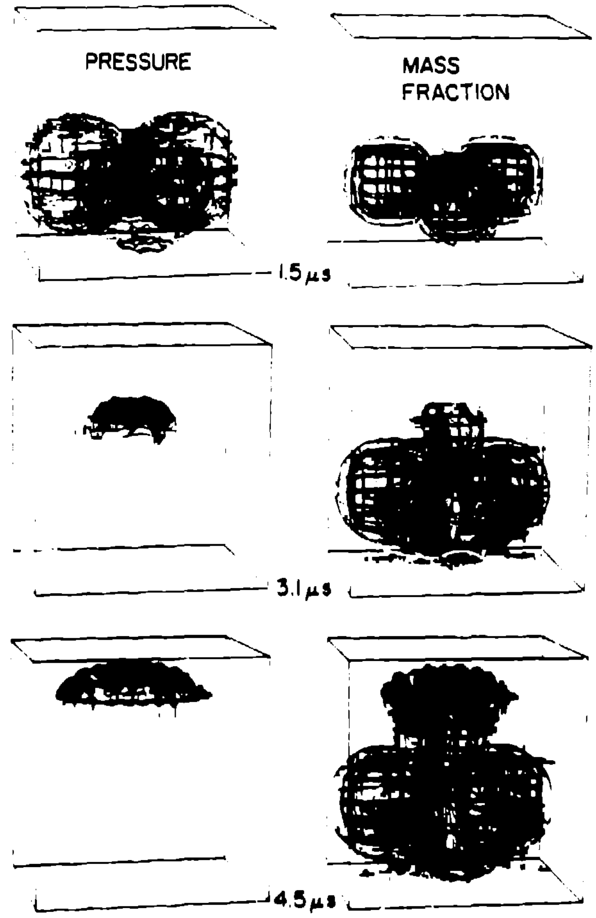


Fig. 12 - The three-dimensional perspective pressure and mass fraction contours for three initiators in PBX-9502. The pressure contours are shown for 200, 150, and 100 kbar at 1.5, 3.1, and 4.5 μs. The mass fraction contours are 0.8 and 0.5.

CONCLUSIONS

The interaction of colliding shock and detonation waves in heterogeneous explosives to form regular and Mach reflections has been investigated both experimentally and theoretically. The characteristics of double, triple, quadruple, and quintuple detonation wave interactions have been numerically modeled using the reactive, three-dimensional Eulerian hydrodynamics code 3DE with Forest Fire kinetics. The high pressure resulting from a triple shock-wave interaction has been shown to result in a propagating detonation in the insensitive explosive PBX-9502 for a system of initiators too weak to initiate the explosive either singly or by the double wave interaction from two of the three initiators.

Numerical modeling of detonation wave interactions of heterogeneous explosives is possible for many systems of complicated two- and three-dimensional geometries and is useful in the design of systems to mitigate or accentuate the high pressures resulting from detonation-wave interactions.

ACKNOWLEDGMENTS

The author wishes to acknowledge the contributions of Douglas Venable and James D. Kershner.

REFERENCES

1. L. V. Al'Tshuler, S. B. Kormer, A. A. Bakanova, A. P. Petrunin, A. I. Funtikov, and A. A. Gubkin, J. Expt. Theoret. Phys. (U.S.S.R.), Vol. 41, pp. 1382-1388, 1961.

2. Charles L. Mader, "Numerical Studies of Regular and Mach Reflection of Shocks in Aluminum," Los Alamos Scientific Laboratory Report LA-3578, Jan. 1967.

3. S. D. Gardner and Jerry Wackerle, "Interactions of Detonation Waves in Condensed Explosives," The Fourth Symposium on Detonation, Office of Naval Research Symposium Report ACR-126, pp. 154 & 155, 1965.

4. B. D. Lamborn and P. W. Wright, "Mach Interaction of Two Plane Detonation Waves," The Fourth Symposium on Detonation, Office of Naval Research Symposium Report ACR-126, pp. 142-151, 1965.

5. Charles L. Mader and Douglas Venable, "Mach Stems Formed by Colliding Cylindrical Detonation Waves," Los Alamos Scientific Laboratory Report LA-7869, Sept. 1979.

6. D. Venable, "PHERMEX," Phys. Today, Vol. 17, No. 12, pp. 19-25, 1964.

7. Charles L. Mader, Numerical Modeling of Detonations, University of California Press, Berkeley, California, 1979.

8. William R. Gage and Charles L. Mader, "Three-Dimensional Cartesian Particle-in-Cell Calculations," Los Alamos Scientific Laboratory Report LA-3422, Jan. 1967.

9. W. E. Johnson, "TRIOIL," Gulf General Atomic, San Diego, Report GAMD-7310, 1967.

10. C. W. Hirt and J. L. Cook, "Calculating Three-Dimensional Flows Around Structures and Over Rough Terrain," J. Comp. Phys., Vol. 10, p. 324, 1972.

11. William E. Pracht, "Calculating Three-Dimensional Fluid Flows at All Speeds with an Eulerian-Lagrangian Computing Mesh," J. Comp. Phys., Vol. 17, p. 132, 1974.

12. W. E. Pracht and J. U. Brackbill, "BAAL: A Code for Calculating Three-Dimensional Fluid Flows at All Speeds with Eulerian-Lagrangian Computing Mesh," Los Alamos Scientific Laboratory Report LA-6342, 1976.

13. L. R. Stein, R. A. Gentry, and C. W. Hirt, "Computational Simulation of Transient Blast Loading on Three-Dimensional Structures," J. Comp. Methods in App. Mech. and Eng., Vol. 11, p. 57, 1977.

14. M. W. Wilkins, S. J. French, and M. Sorem, "Finite Difference Scheme for Calculating Problems in Three Space Dimensions and Time," Second International Conference on Numerical Methods in Fluid Dynamics, University of California, Berkeley, September 15-19, 1970.

15. Charles L. Mader and James D. Kershner, "Three-Dimensional Eulerian Calculations of Triple-Initiated PBX-9404," Los Alamos Scientific Laboratory Report LA-8206, Sept. 1980.

16. J. H. Goforth, "Safe-Stationary Detonation Train for Army Ordnance," Los Alamos Scientific Laboratory Report LA-7123-MS, March 1978.

17. Charles L. Mader, "Numerical Modeling of Insensitive High-Explosive Initiators," Los Alamos Scientific Laboratory Report LA-8437-MS, July 1980.

18. Charles L. Mader and James D. Kershner, "Three-Dimensional Modeling of Triple-Wave Initiation of Insensitive Explosives," Los Alamos National Laboratory Report LA-8655, 1981.